Hadron Form Factors and DSEs

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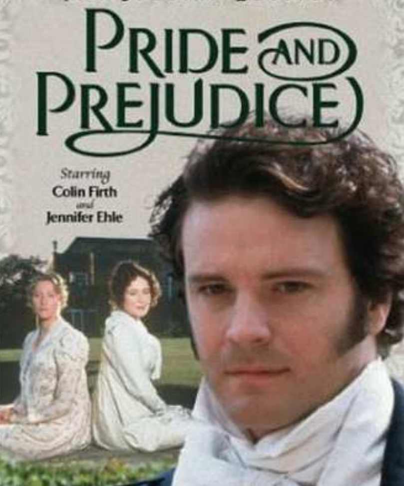
http://www.phy.anl.gov/theory/staff/cdr.html

Universal Truths



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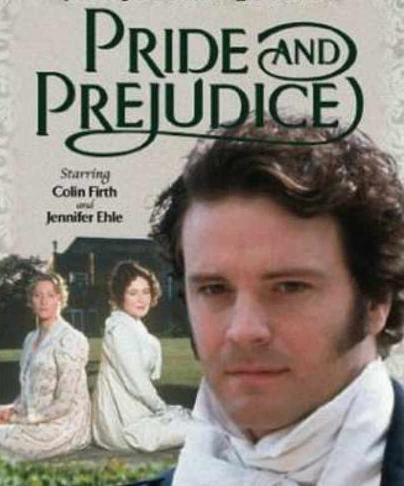

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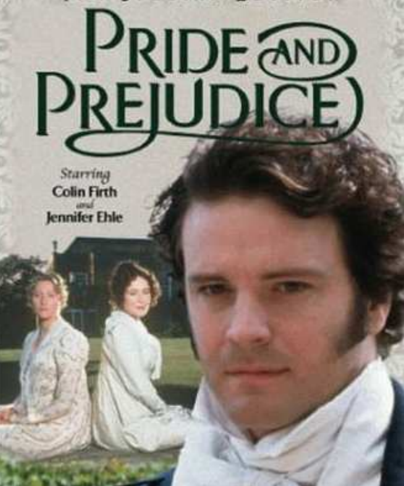

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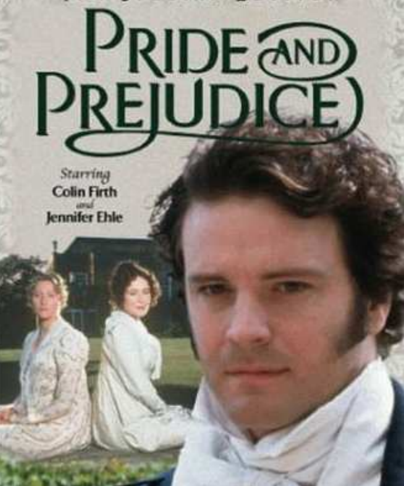

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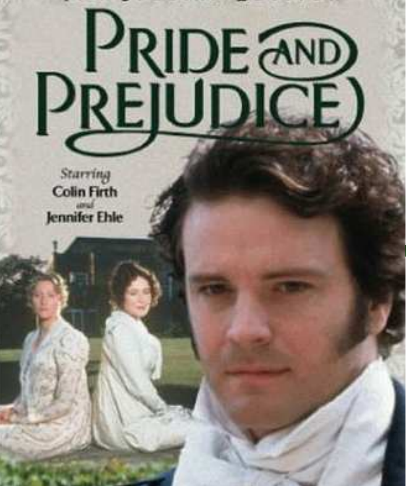

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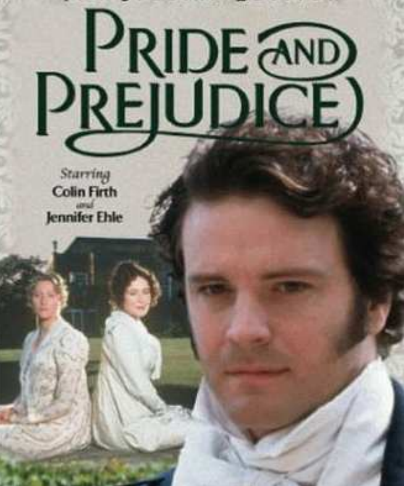

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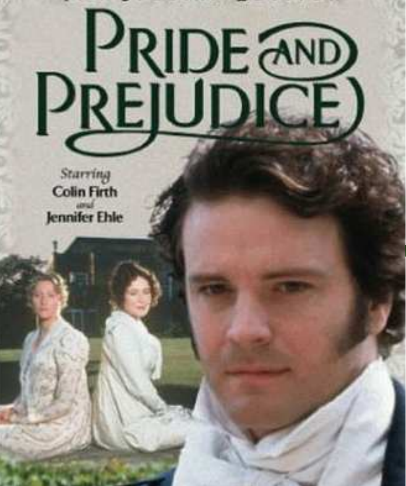

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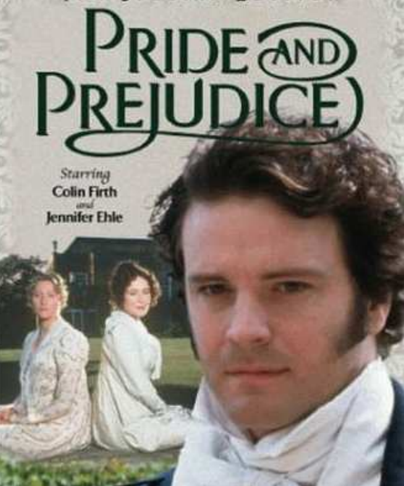

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- Challenge: understand relationship between parton properties on the light-front and rest frame structure of hadrons. Problem because, e.g., DCSB - an established keystone of low-energy QCD and the origin of constituent-quark masses - has not been realised in the light-front formulation.

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Understand Emergent Phenomena

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- QCD – Complex behaviour

  arises from apparently simple rules

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- Experimental and theoretical studies of nucleon electromagnetic form factors have made rapid and significant progress during the last several years, including new data in the time like region, and material gains have been made in studying the pion form factor.
- Despite this, many urgent questions remain unanswered.

Some Questions

- What is the role of pion cloud in nucleon electromagnetic structure?
- Can we understand the pion cloud in a more quantitative and, perhaps, model-independent way?

Some Questions

- Where is the transition from non-pQCD to pQCD in the pion and nucleon electromagnetic form factors?

Some Questions

- Do we understand the high Q^2 behavior of the proton form factor ratio in the space-like region?
- Can we make model-independent statements about the role of relativity or orbital angular momentum in the nucleon?

Some Questions

- Can we understand the rich structure of the time-like proton form factors in terms of resonances?
- What do we expect for the proton form factor ratio in the time-like region?
- What is the relation between proton and neutron form factor in the time-like region?
- How do we understand the ratio between time-like and space-like form factors?

Some Questions

- What is the role of two-photon exchange contributions in understanding the discrepancy between the polarization and Rosenbluth measurements of the proton form factor ratio?
- What is the impact of these contributions on other form factor measurements?

Some Questions

- How accurately can the pion form factor be extracted from the $ep \to e'n\pi^+$ reaction?

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- Most recently:
  "ECT* Workshop on Hadron Electromagnetic Form Factors"
  Organisers: Alexandrou, Arrington, Friedrich, Maas, Roberts
  Presentations, etc., available on-line
  http://ect08.phy.anl.gov/

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Highly Nontrivial

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- Must similarly require prediction of $\gamma^*\pi \to \pi\pi$ and all other anomalous processes

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  - Interaction between quarks – the Interquark "Potential" – unknown throughout $>$ 98% of a hadron's volume

Intranucleon Interaction

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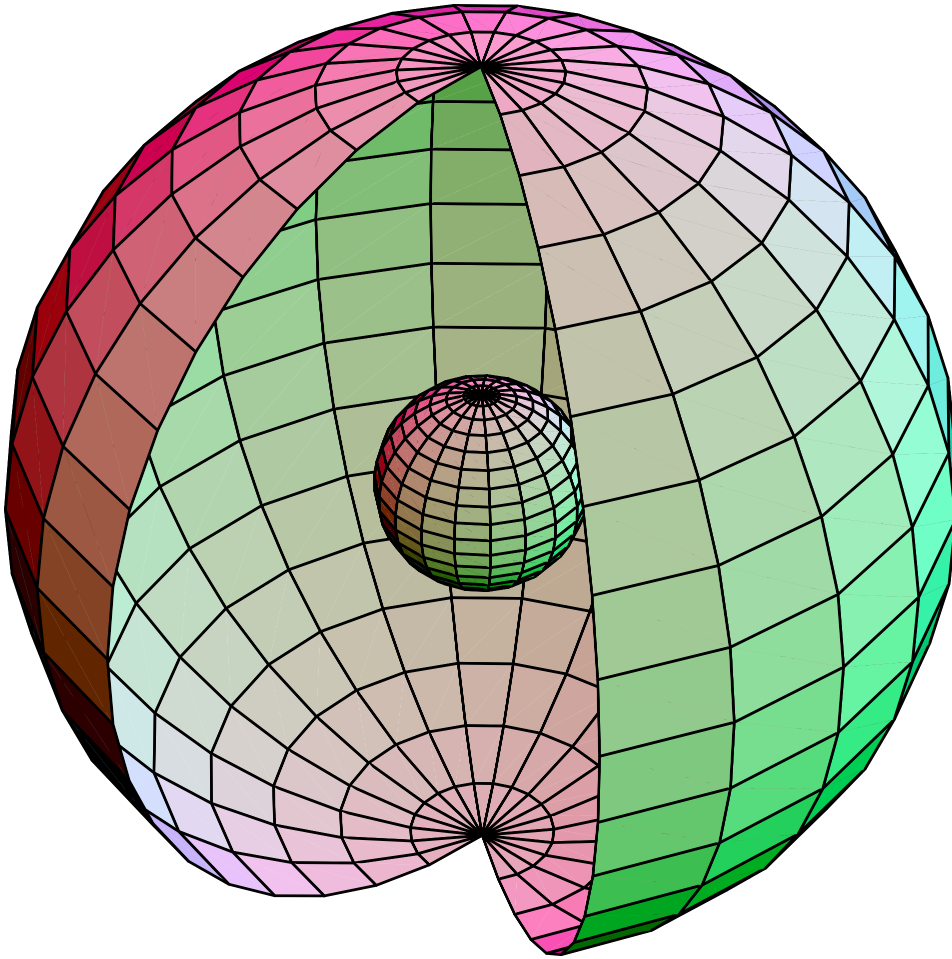

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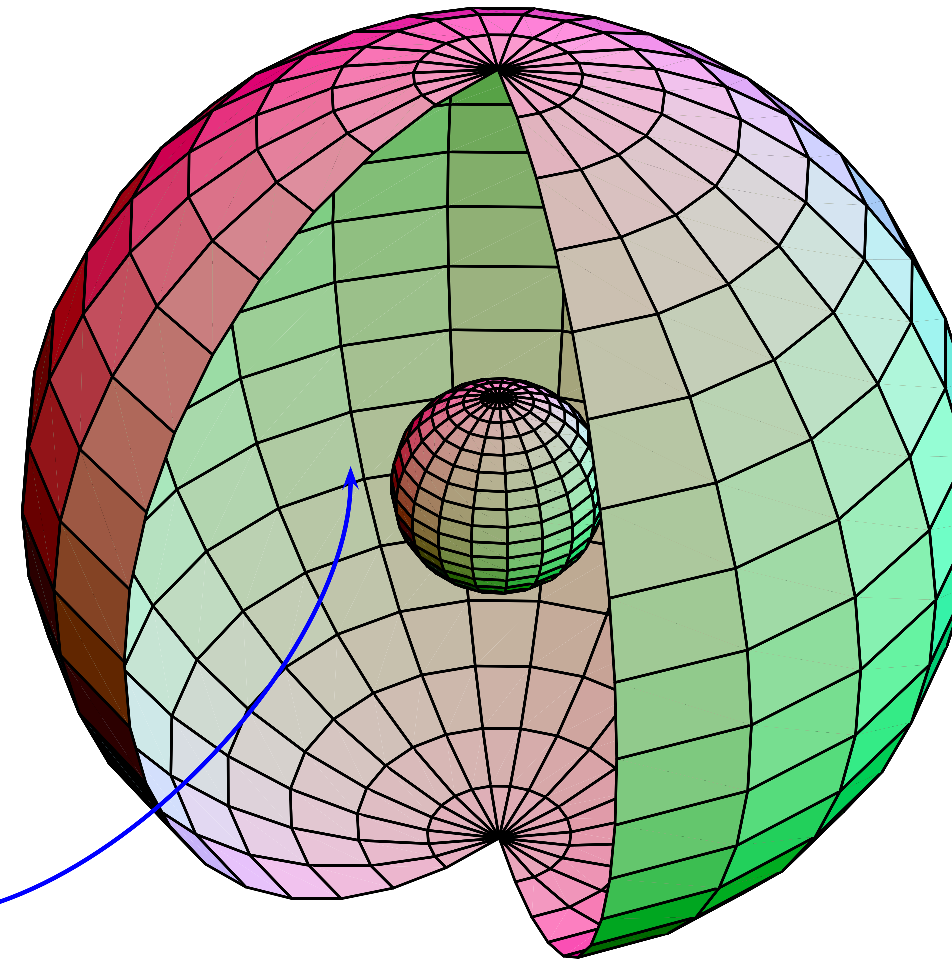
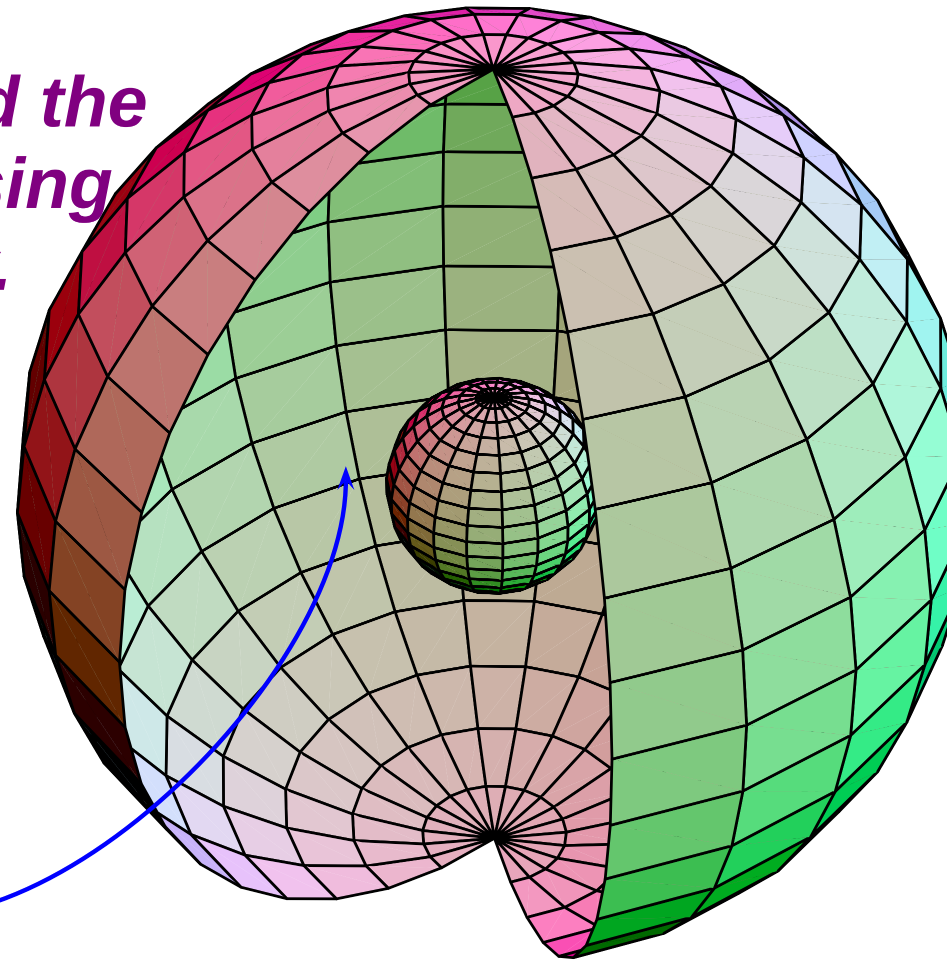


98% of the volume

What is the Intranucleon Interaction?

The question must be rigorously defined, and the answer mapped out using experiment and theory.



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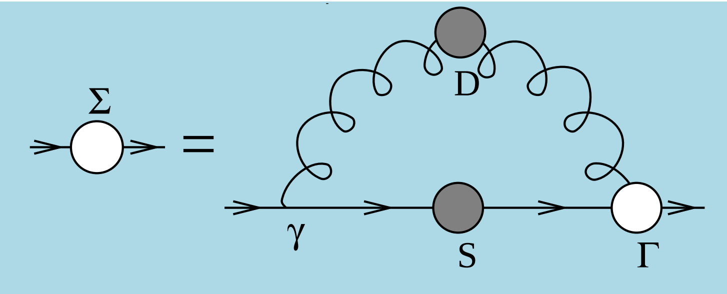

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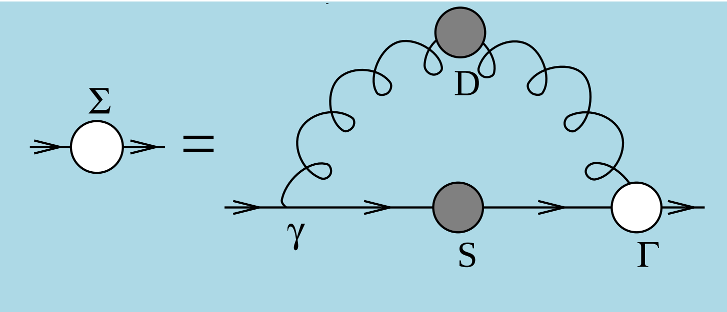

Gap Equation

- Gap Equation's Kernel Enhanced on IR domain

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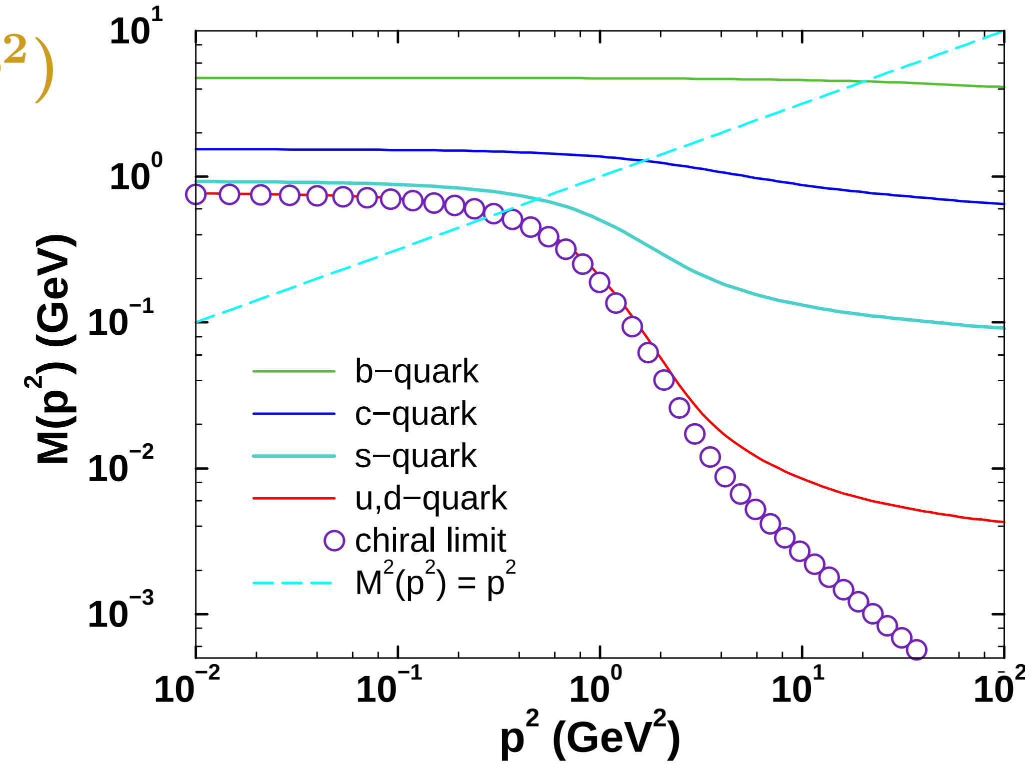

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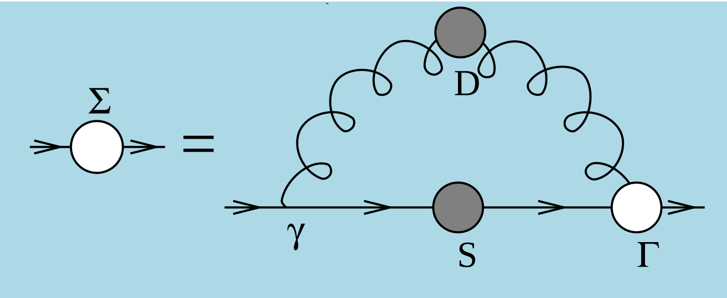

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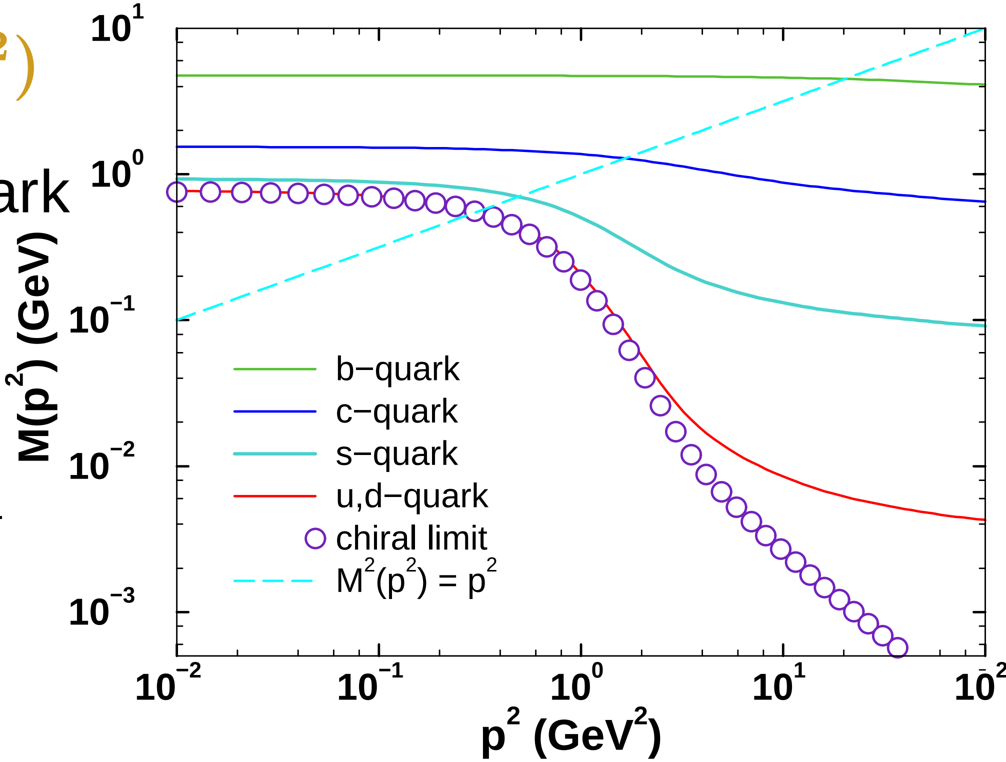

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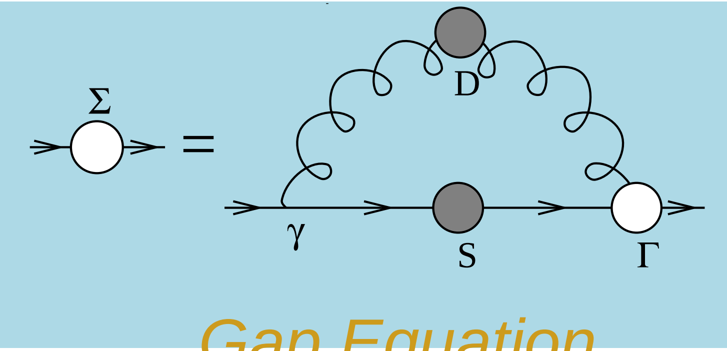

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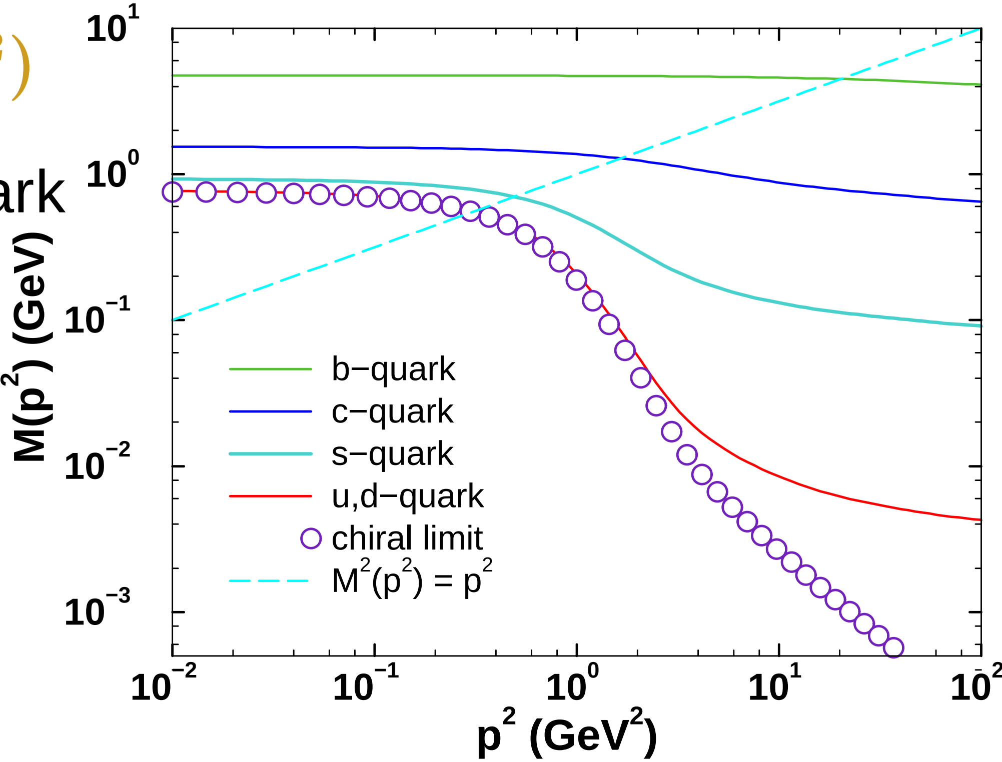
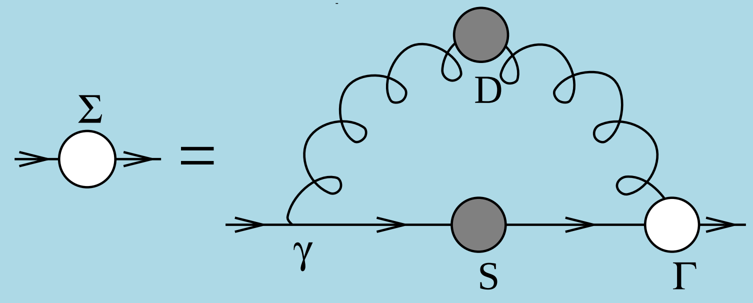


Predictions confirmed in numerical simulations of lattice-QCD

Frontiers of Nuclear Science: A Long Range Plan (2007)



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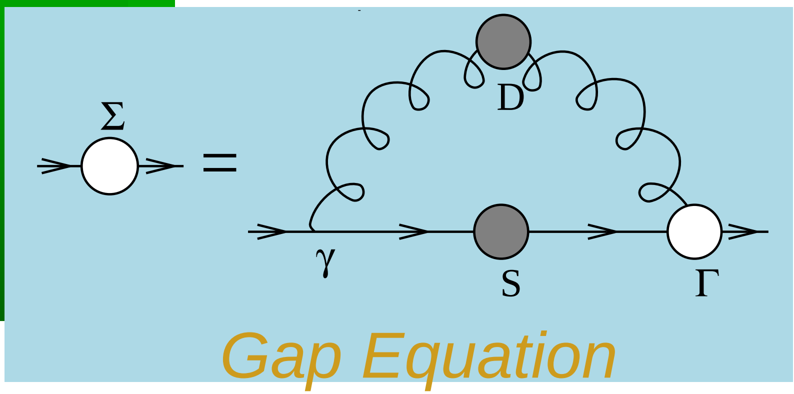

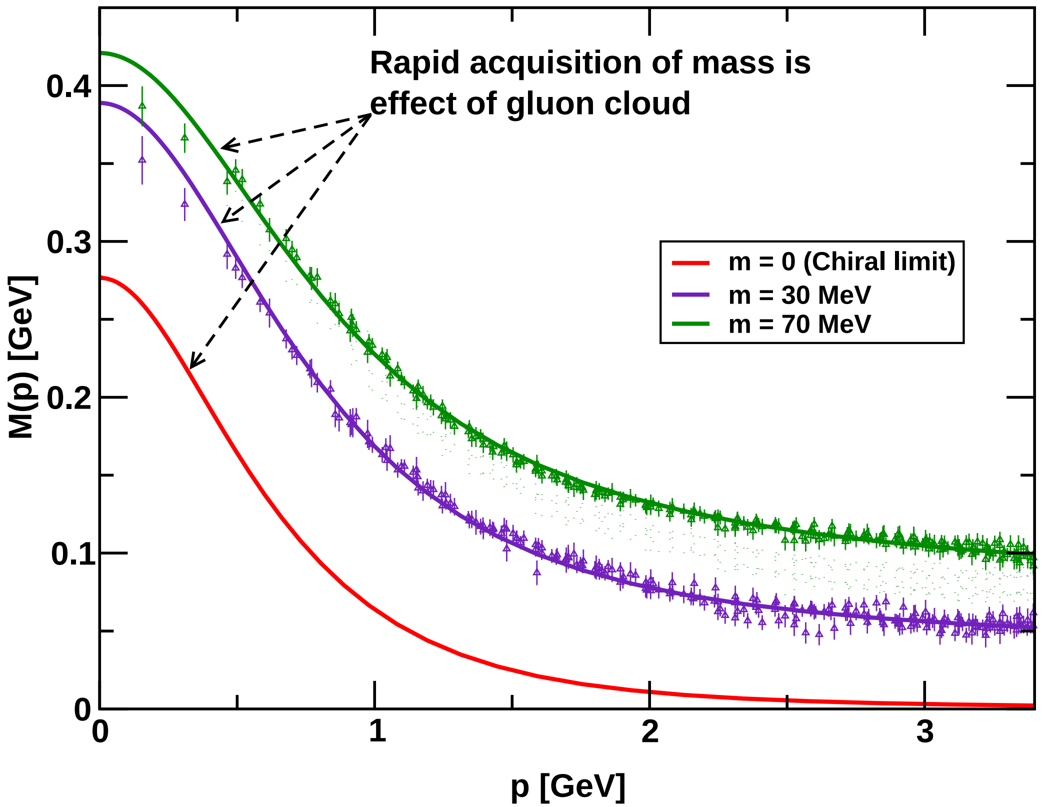

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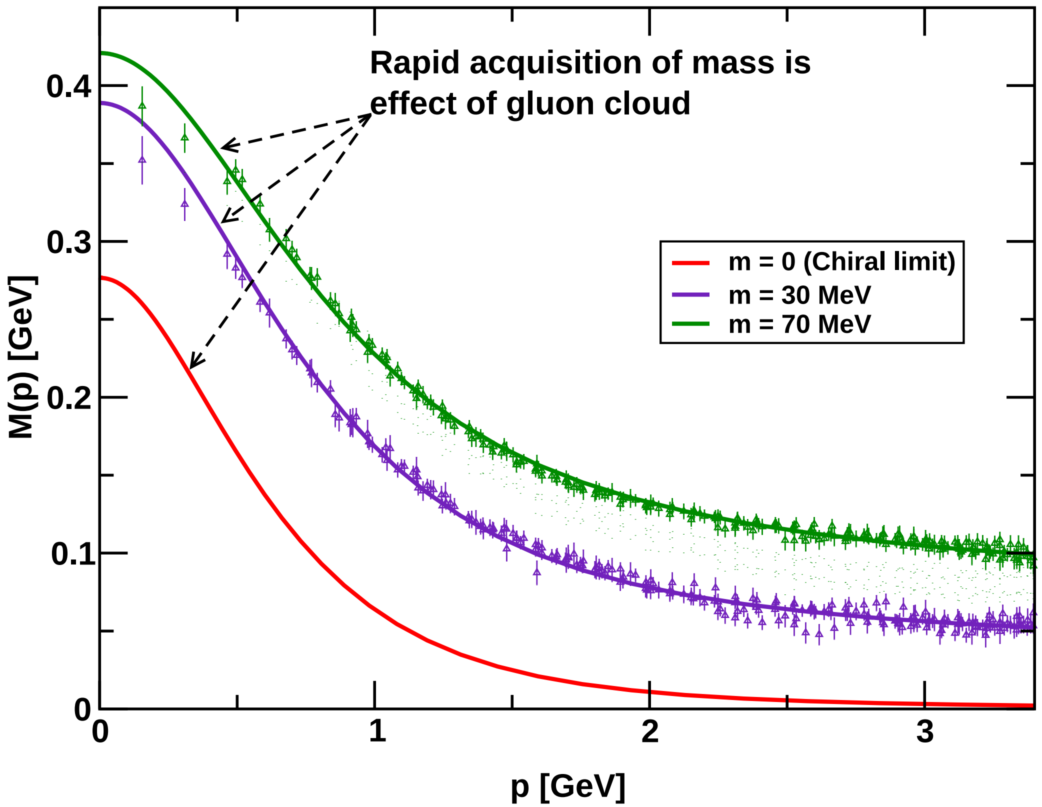

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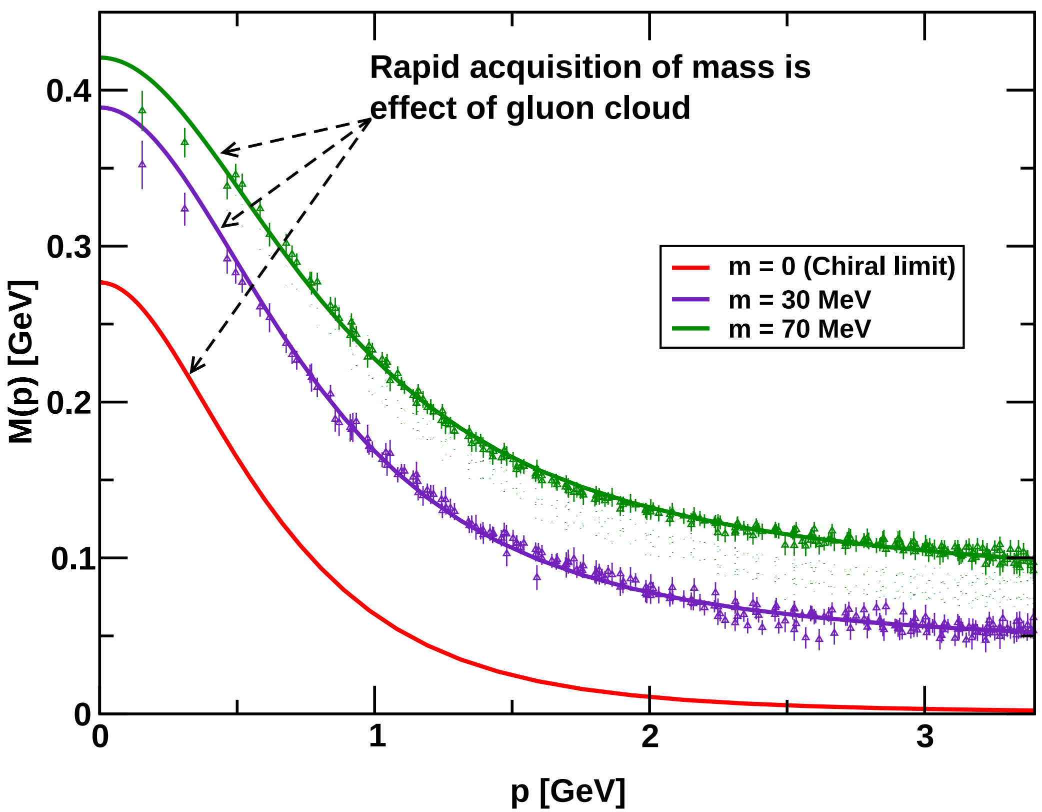

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- What about bound states?

Hadrons

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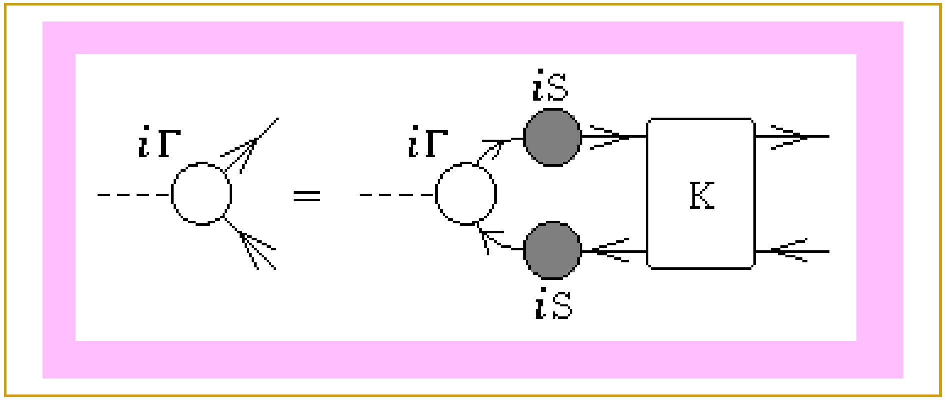

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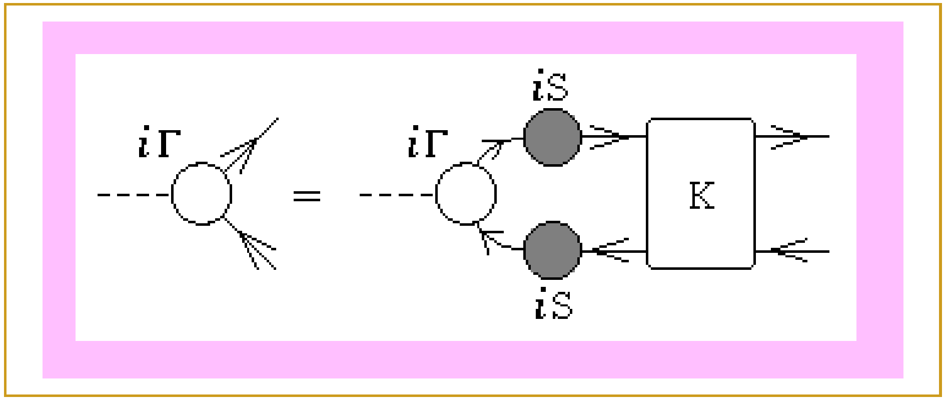

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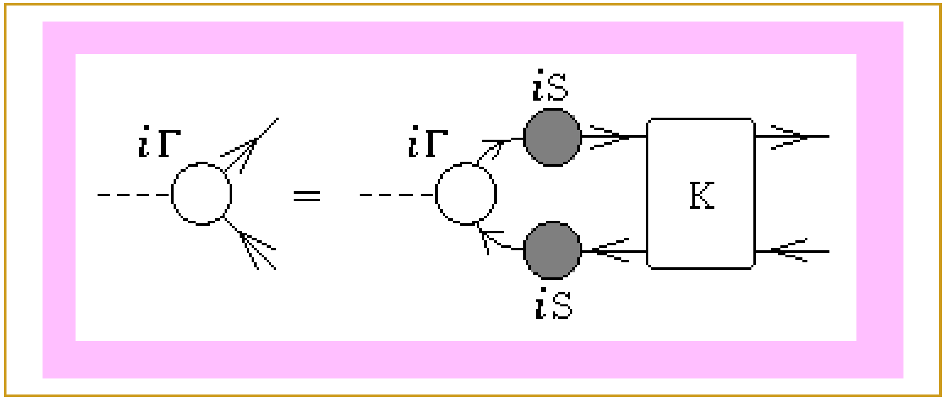

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or

What is the light-quark Long-Range Potential?

What is the light-quark Long-Range Potential?

Potential between static (infinitely heavy) quarks measured in simulations of lattice-QCD ***is not related*** in any simple way to the light-quark interaction.

Bethe-Salpeter Kernel

- Axial-vector Ward-Takahashi identity

$$P_\mu \, \Gamma^l_{5\mu}(k;P) \quad = \quad \mathcal{S}^{-1}(k_+)\,\frac{1}{2}\lambda^l_f i\gamma_5 + \frac{1}{2}\lambda^l_f i\gamma_5 \;\; \mathcal{S}^{-1}(k_-)$$

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QFT Statement of Chiral Symmetry

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- Relation must be preserved by truncation

Bethe-Salpeter Kernel

- Axial-vector Ward-Takahashi identity

$$P_\mu \Gamma^l_{5\mu}(k;P) \;=\; \mathcal{S}^{-1}(k_+)\,\frac{1}{2}\lambda^l_f i\gamma_5 + \frac{1}{2}\lambda^l_f i\gamma_5\,\mathcal{S}^{-1}(k_-)$$

$$-M_\zeta\, i\Gamma^l_5(k;P) - i\Gamma^l_5(k;P)\, M_\zeta$$

Satisfies BSE   Satisfies DSE

Kernels very different

but must be intimately related

- Relation must be preserved by truncation
- Nontrivial constraint

- Axial-vector Ward-Takahashi identity

$$P_\mu \Gamma^l_{5\mu}(k;P) \;=\; \mathcal{S}^{-1}(k_+)\,\frac{1}{2}\lambda^l_f i\gamma_5 + \frac{1}{2}\lambda^l_f i\gamma_5\,\mathcal{S}^{-1}(k_-)$$
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Satisfies BSE　　　　　　　　Satisfies DSE

Kernels very different

but must be intimately related

- Relation must be preserved by truncation
- Failure $\Rightarrow$ Explicit Violation of QCD's Chiral Symmetry

Persistent Challenge

- Infinitely Many Coupled Equations
- There is at least one systematic nonperturbative, symmetry-preserving truncation scheme

  H.J. Munczek Phys. Rev. D **52** (1995) 4736

  Dynamical chiral symmetry breaking, Goldstone's theorem and the consistency of the Schwinger-Dyson and Bethe-Salpeter Equations

  A. Bender, C. D. Roberts and L. von Smekal, Phys. Lett. B **380** (1996) 7

  Goldstone Theorem and Diquark Confinement Beyond Rainbow Ladder Approximation

Persistent Challenge

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  - Make Predictions with Readily Quantifiable Errors

Radial Excitations & Chiral Symmetry

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Radial Excitations & Chiral Symmetry

$$\boxed{f_H \;\; m_H^2 = - \;\; \rho_\zeta^H \;\; \mathcal{M}_H}$$

Radial Excitations & Chiral Symmetry

(Maris, Roberts, Tandy nu-th/9707003)

$$\boxed{f_H \;\; m_H^2 = - \;\; \rho_\zeta^H \;\; \mathcal{M}_H}$$

- Mass^2 of pseudoscalar hadron

(Maris, Roberts, Tandy nu-th/9707003)

$$\boxed{f_H \;\; m_H^2 = - \;\; \rho_\zeta^H \;\; \mathcal{M}_H}$$

$$\mathcal{M}_H := \mathrm{tr}_{\mathrm{flavour}} \left[M_{(\mu)} \left\{ T^H, \left(T^H\right)^{\mathrm{t}} \right\} \right] = m_{q_1} + m_{q_2}$$

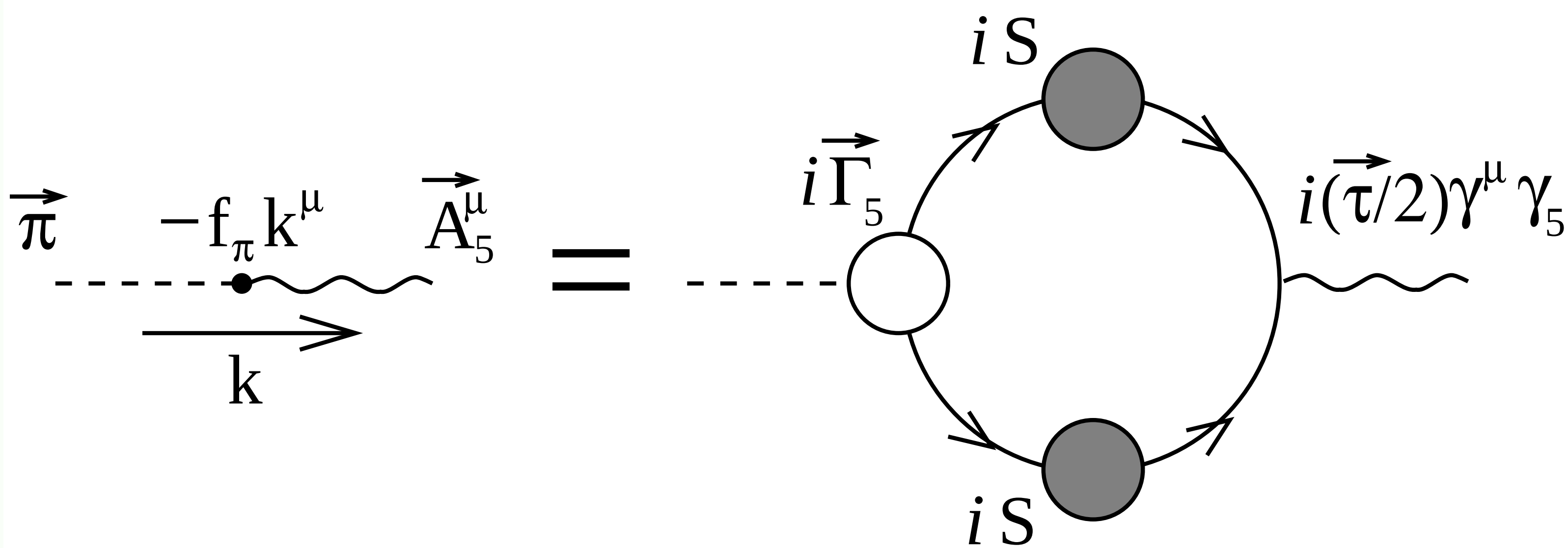
- Sum of constituents' current-quark masses
- e.g., $T^{K^+} = \frac{1}{2}\left(\lambda^4 + i\lambda^5\right)$

(Maris, Roberts, Tandy nu-th/9707003)

$$\boxed{f_H\, m_H^2 = -\ \rho_\zeta^H\ \ \mathcal{M}_H}$$

$$f_H\, p_\mu = Z_2 \int_q^\Lambda \tfrac{1}{2}\mathrm{tr}\left\{ \left(T^H\right)^{\mathrm{t}} \gamma_5\gamma_\mu \boxed{\mathcal{S}(q_+)\Gamma_H(q;P)\mathcal{S}(q_-)} \right\}$$

- Pseudovector projection of BS wave function at $x = 0$
- Pseudoscalar meson's leptonic decay constant



Radial Excitations & Chiral Symmetry

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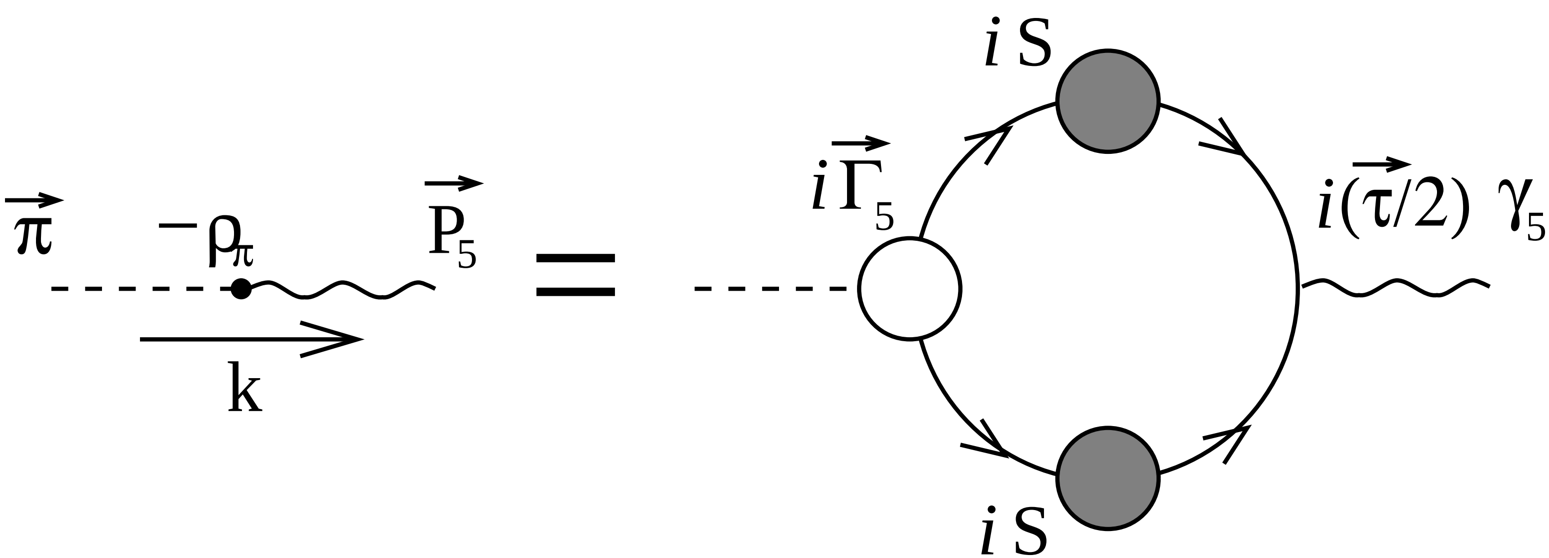

Radial Excitations & Chiral Symmetry

$$\boxed{f_H \;\; m_H^2 = - \;\; \rho_\zeta^H \;\; \mathcal{M}_H}$$

- Light-quarks; i.e., $m_q \sim 0$
  - $f_H \to f_H^0$ & $\rho_\zeta^H \to \dfrac{-\langle \bar{q}q \rangle_\zeta^0}{f_H^0}$, Independent of m_q

Hence $\boxed{m_H^2 = \dfrac{-\langle \bar{q}q \rangle_\zeta^0}{(f_H^0)^2}\, m_q}$ ...GMOR relation, a corollary

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Hence $\boxed{m_H^2 = \dfrac{-\langle \bar{q} q \rangle_\zeta^0}{(f_H^0)^2} m_q}$ . . . GMOR relation, a corollary

- Heavy-quark + light-quark

$\Rightarrow f_H \propto \dfrac{1}{\sqrt{m_H}}$ and $\rho_\zeta^H \propto \sqrt{m_H}$

Hence, $\boxed{m_H \propto m_q}$

. . . QCD Proof of Potential Model result

Radial Excitations & Chiral Symmetry

Höll, Krassnigg, Roberts
nu-th/0406030

$$f_H \;\; m_H^2 = - \;\; \rho_\zeta^H \;\; \mathcal{M}_H$$

- Valid for ALL Pseudoscalar mesons

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ALL pseudoscalar mesons except $\boldsymbol{\pi(140)}$ in chiral limit

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- $\Rightarrow f_H = 0$

  ALL pseudoscalar mesons except $\pi(140)$ in chiral limit
- Dynamical Chiral Symmetry Breaking

  – Goldstone's Theorem –

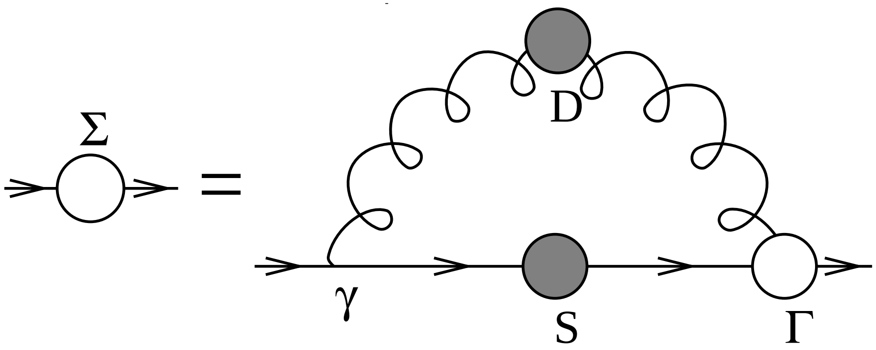
  impacts upon *every* pseudoscalar meson

Procedure Now Straightforward

Pion Form Factor

- Solve Gap Equation

  $\Rightarrow$ Dressed-Quark Propagator, $S(p)$



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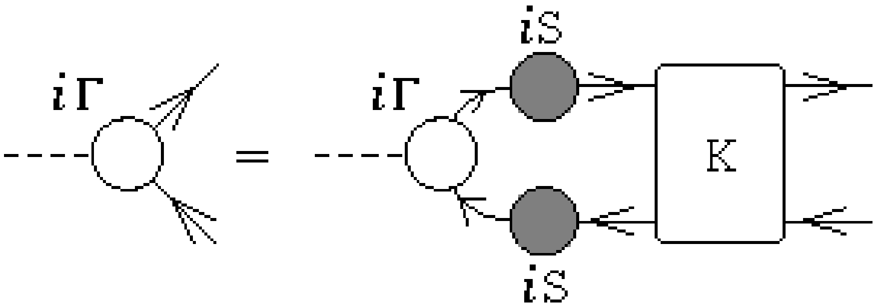
Pion Form Factor

- Use that to Complete Bethe Salpeter Kernel, K
- Solve Homogeneous Bethe-Salpeter Equation for Pion Bethe-Salpeter Amplitude, Γ_π



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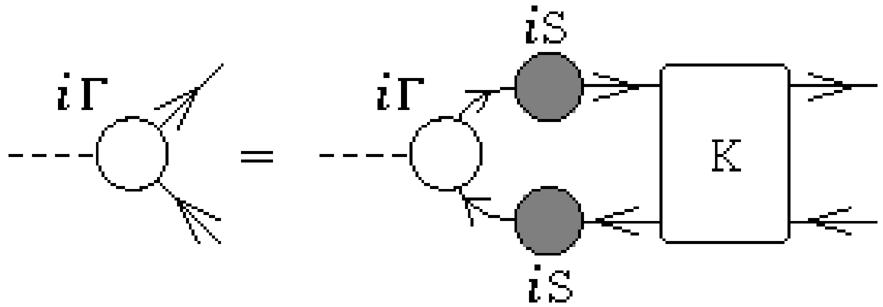
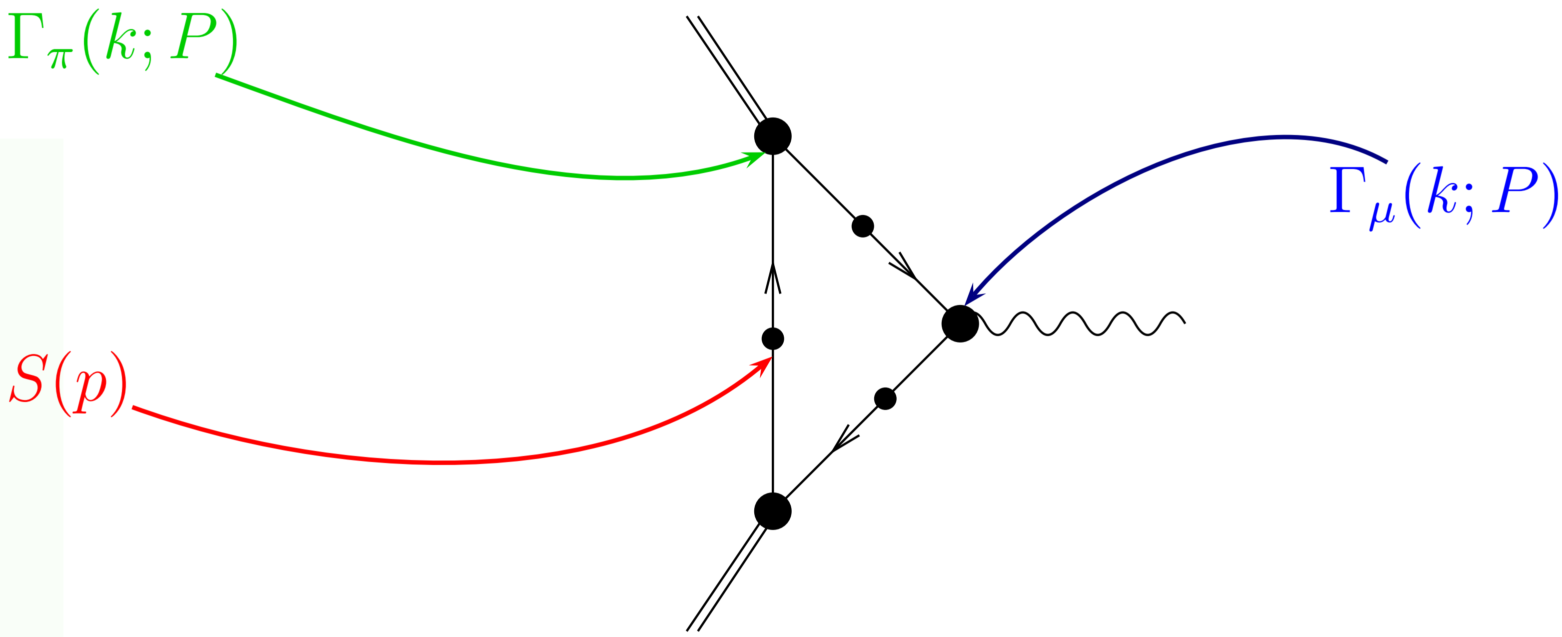


- Solve Inhomogeneous Bethe-Salpeter Equation for Dressed-Quark-Gluon Vertex, Γ_μ

Pion Form Factor

- Now have all elements for Impulse Approximation to Electromagnetic Pion Form factor



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Pion Form Factor

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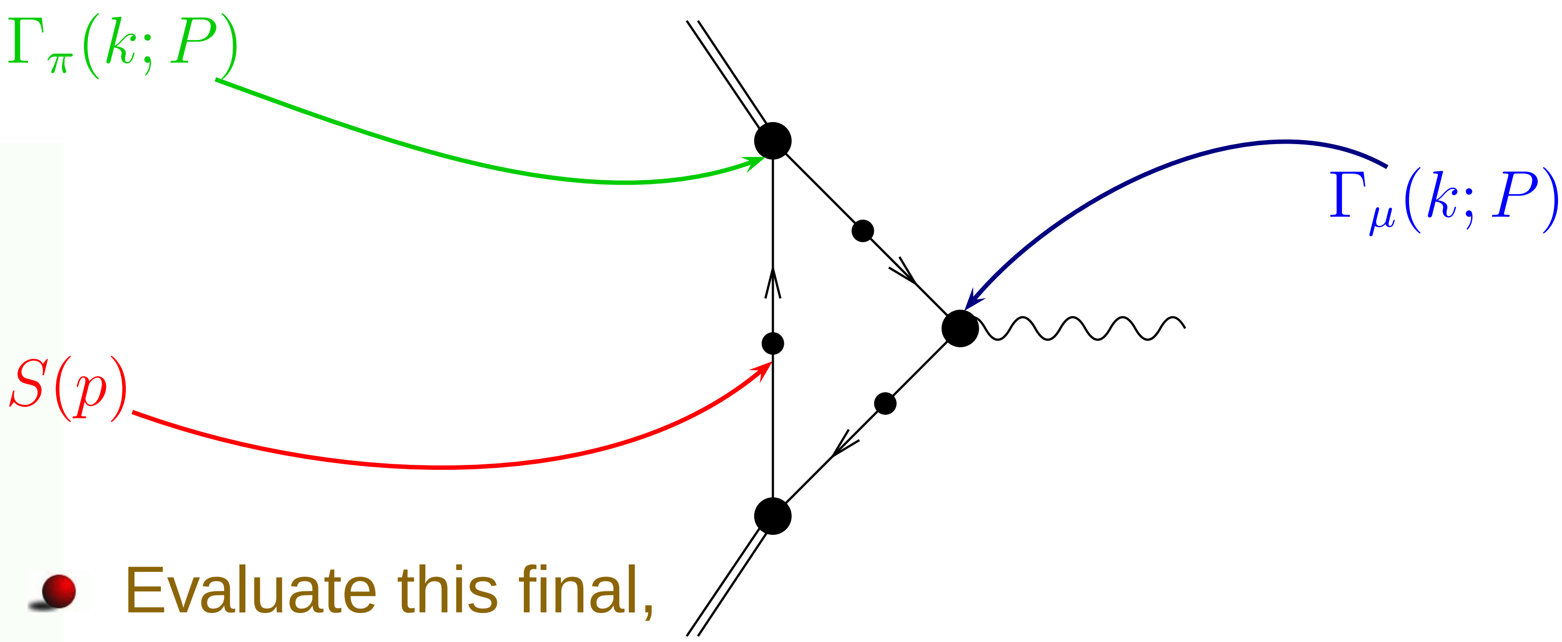
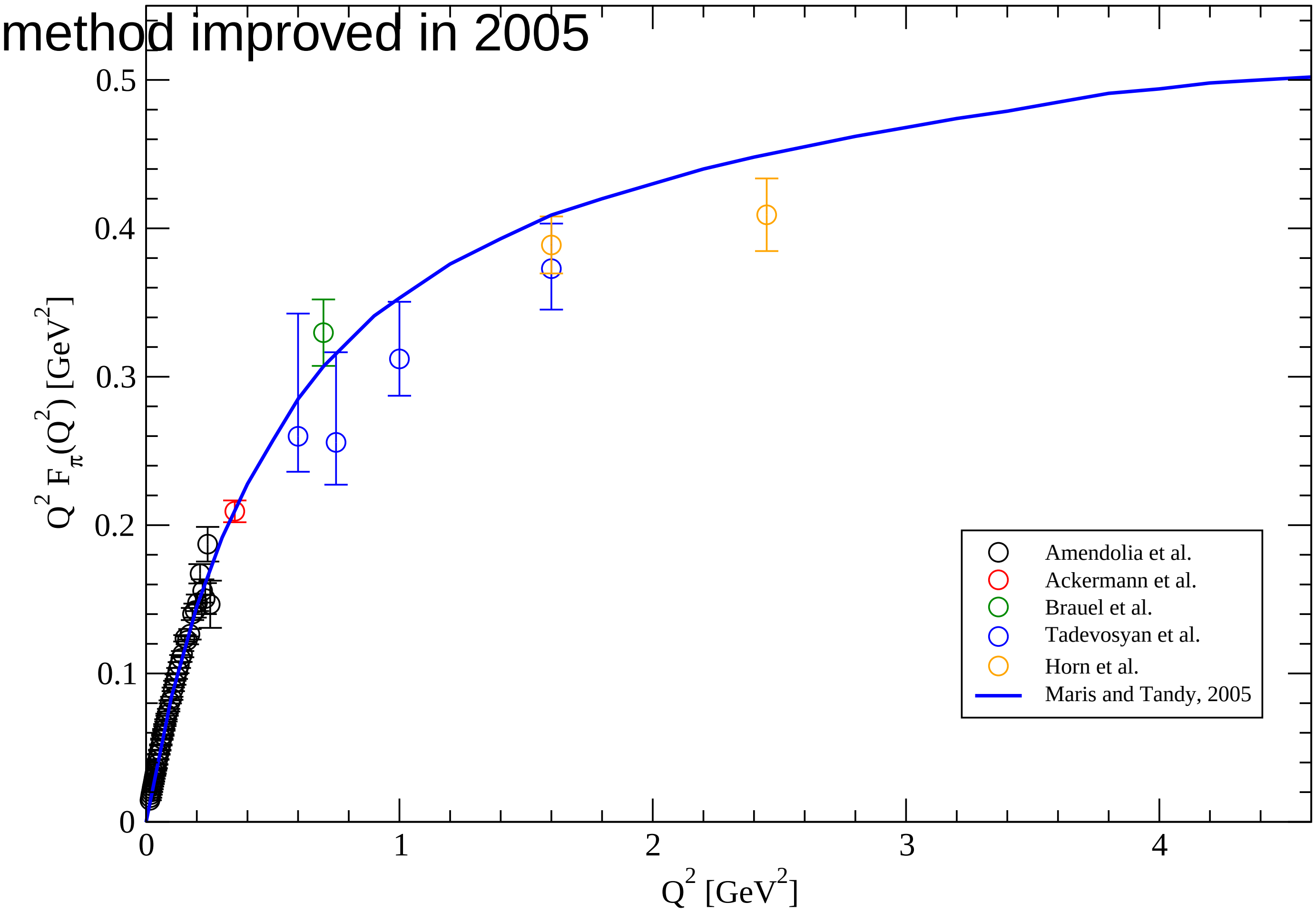


- Evaluate this final, three-dimensional integral

Calculated Pion Form Factor

Calculation first published in 1999; No Parameters Varied

Numerical method improved in 2005



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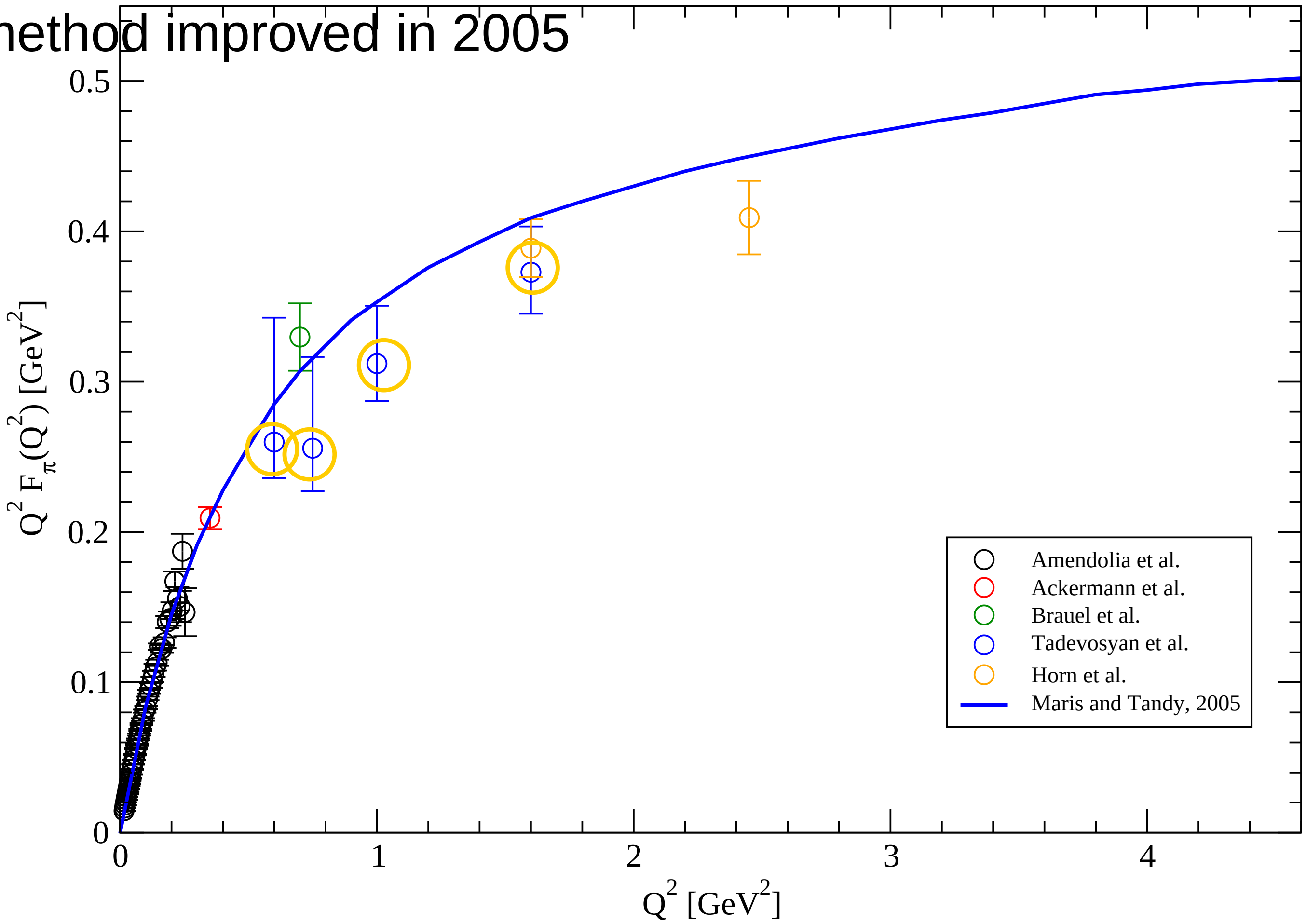
Data published in 2001. Subsequently revised



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Timelike Pion Form Factor

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Timelike Pion Form Factor

Ab initio calculation into timelike region

Deeper than ground-state ρ-meson pole

Timelike Pion Form Factor

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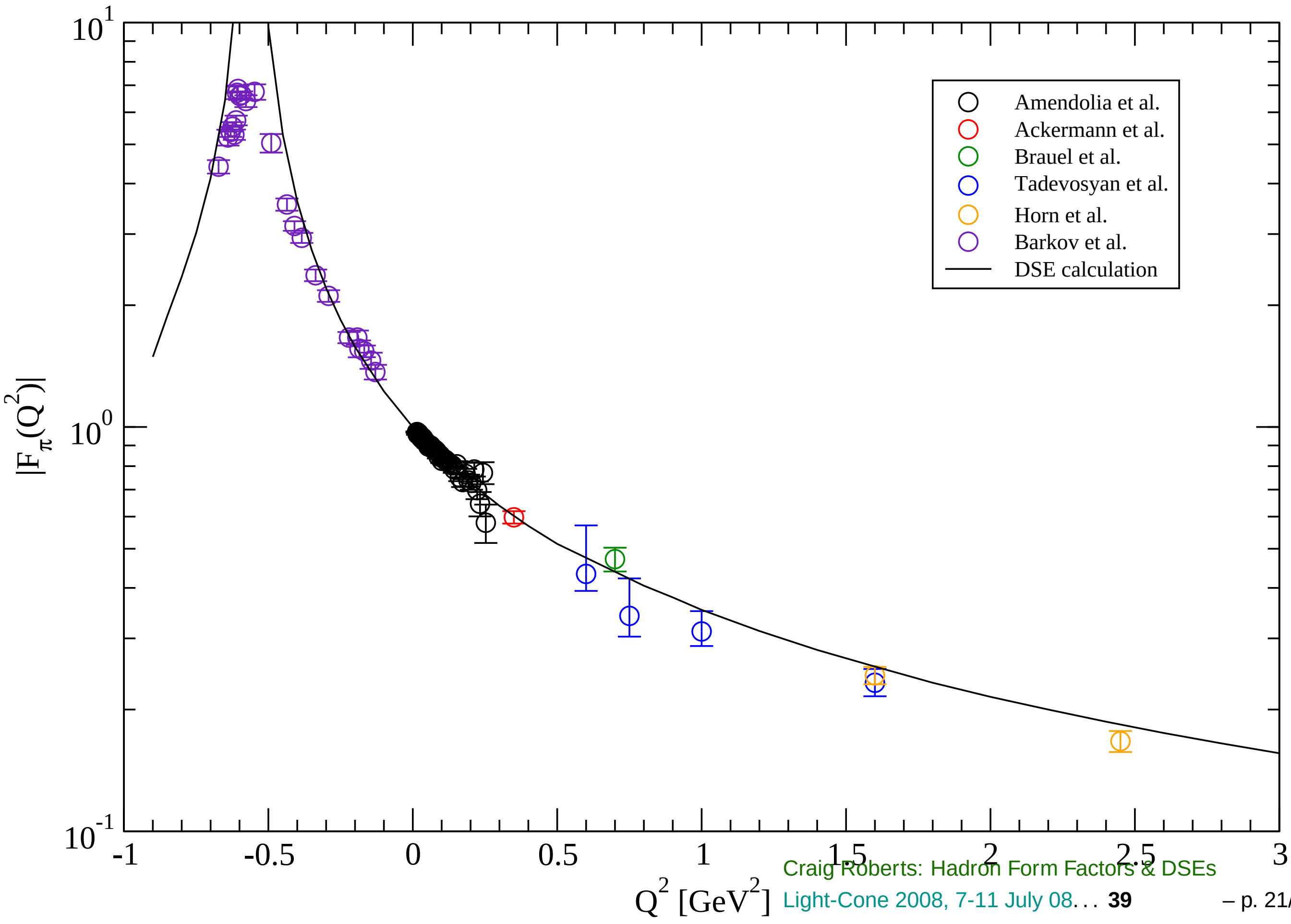
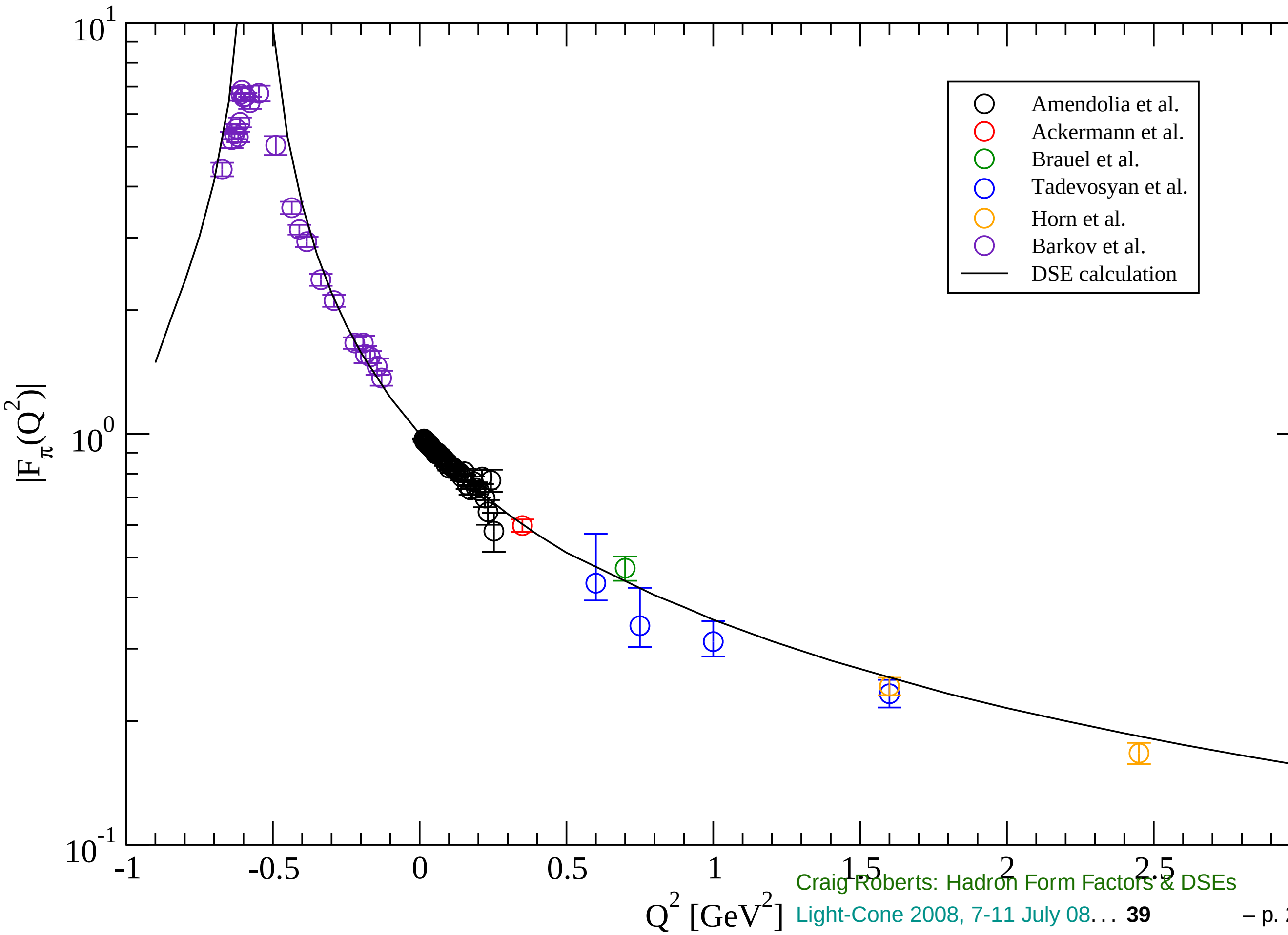


Timelike Pion Form Factor

Ab initio calculation into timelike region

Deeper than ground-state ρ-meson pole

ρ-meson not put in "by hand" – generated dynamically as a bound-state of dressed-quark and dressed-antiquark



Dimensionless product: $r_\pi f_\pi$

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Dimensionless product: $r_\pi \, f_\pi$

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Dimensionless product: $r_\pi\, f_\pi$

- Improved rainbow-ladder interaction

Dimensionless product: $r_\pi \, f_\pi$

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- Repeating $F_\pi(Q^2)$ calculation

Dimensionless product: $r_\pi\, f_\pi$

- Improved rainbow-ladder interaction
- Repeating $F_\pi(Q^2)$ calculation
- Great strides towards placing nucleon studies on same footing as mesons

Dimensionless product: $r_\pi\, f_\pi$

- Improved rainbow-ladder interaction
- Repeating $F_\pi(Q^2)$ calculation
- Experimentally: $r_\pi f_\pi = 0.315 \pm 0.005$

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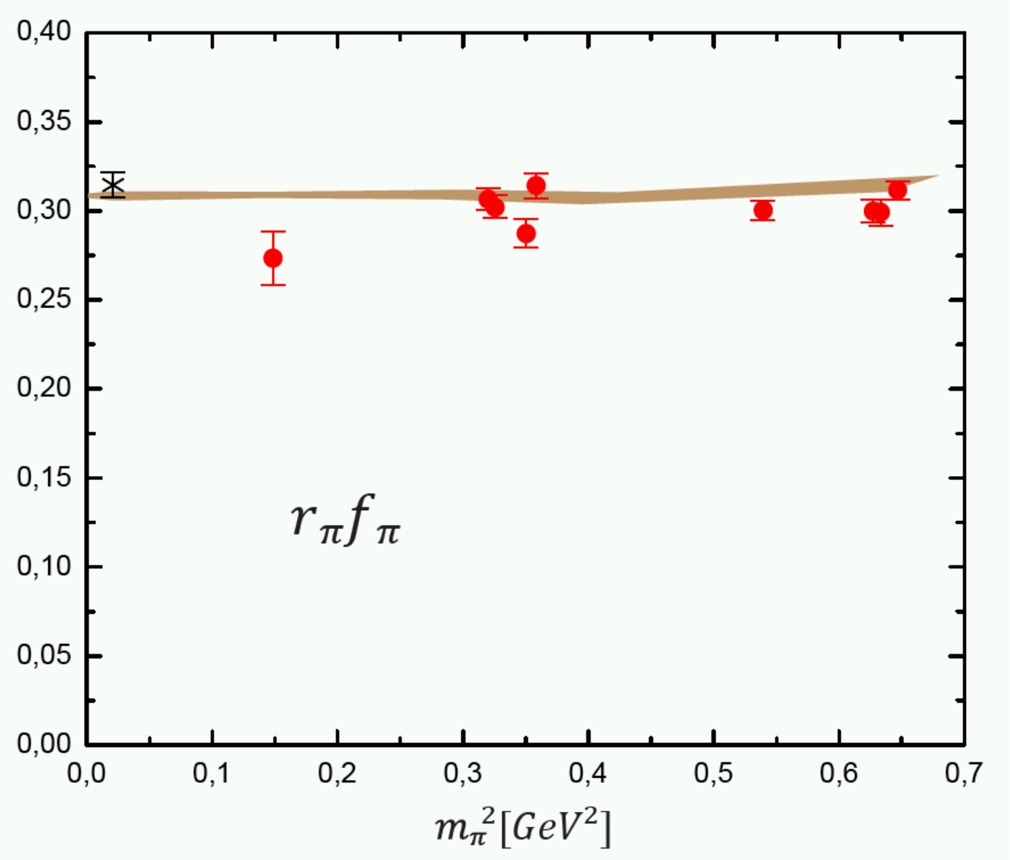
- DSE prediction



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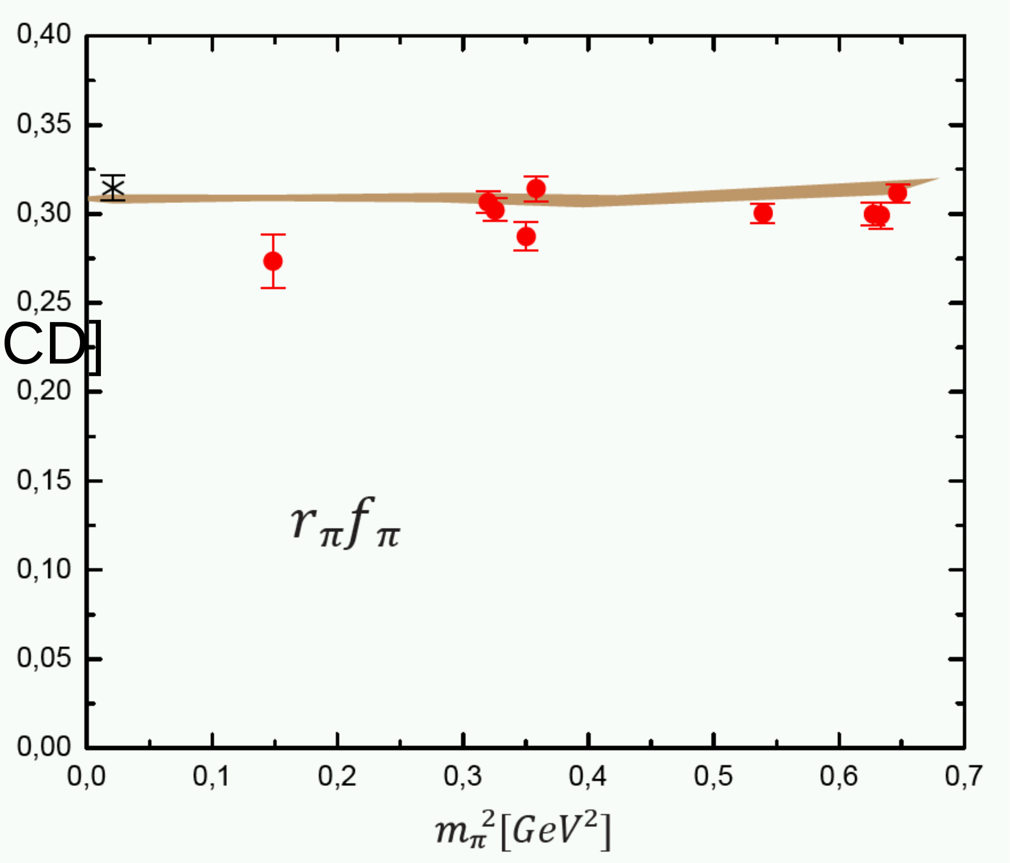

- DSE prediction
- Lattice results
  – James Zanotti [UK QCD]

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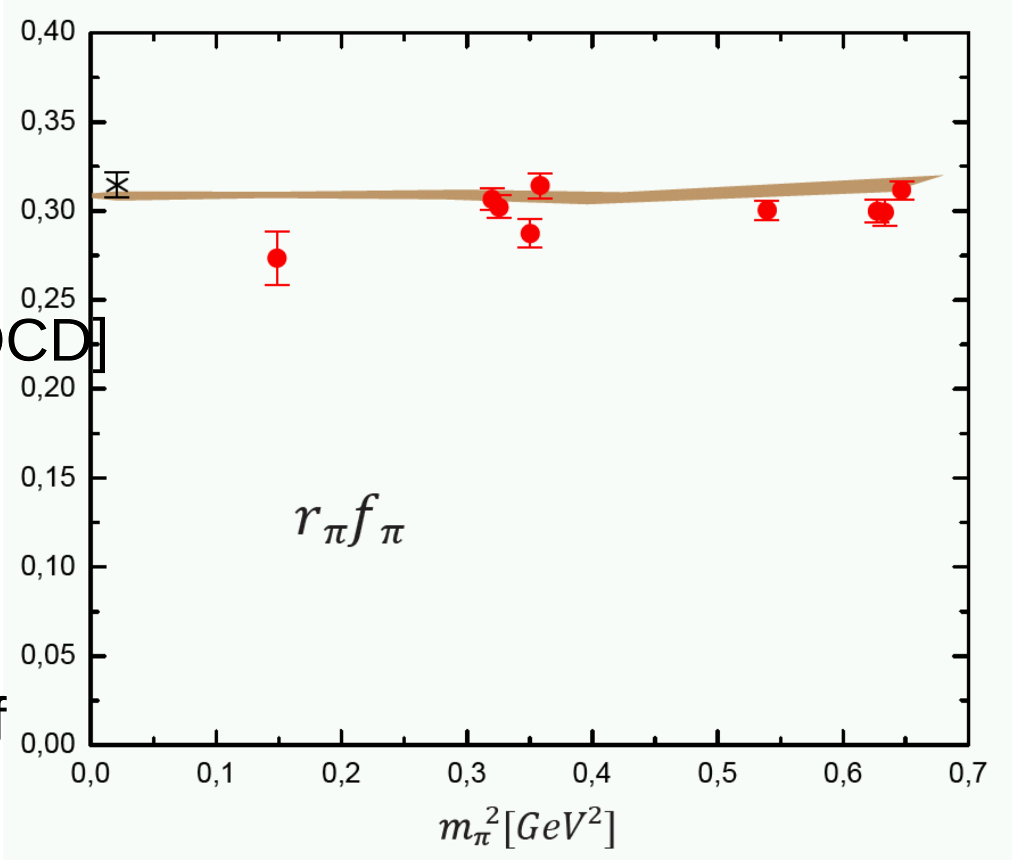
- Fascinating result:
  DSE and Lattice
  – Experimental value obtains independent of current-quark mass.



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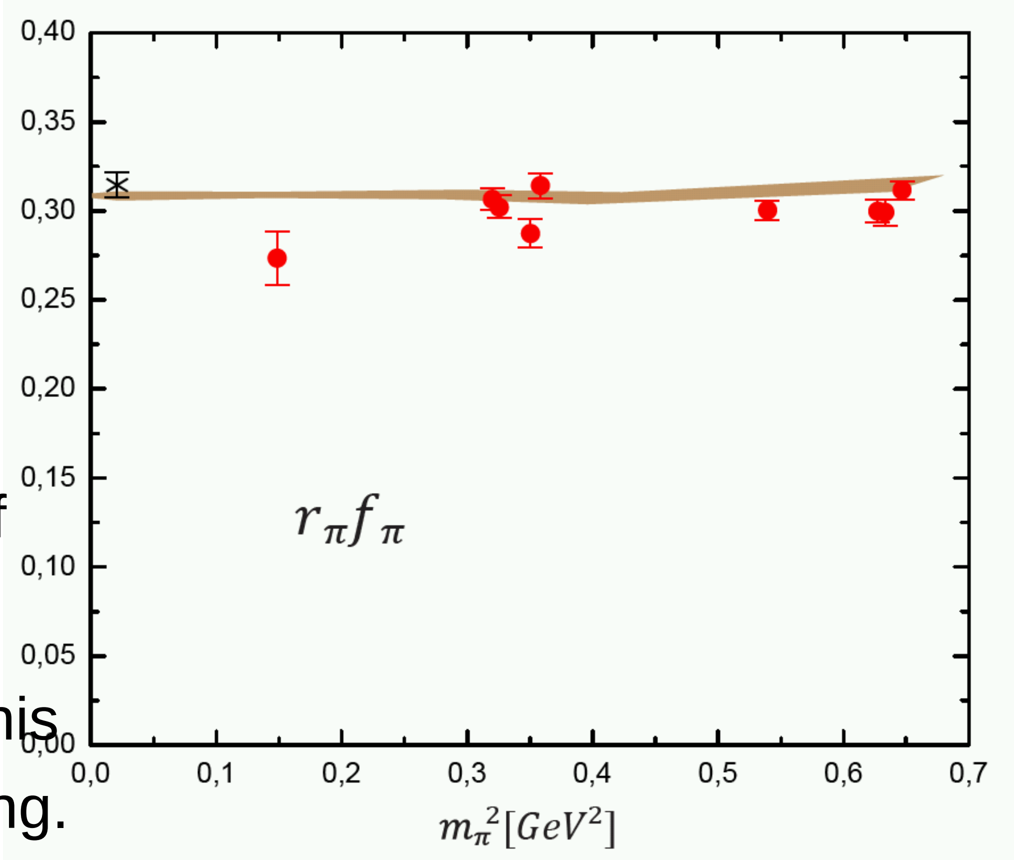
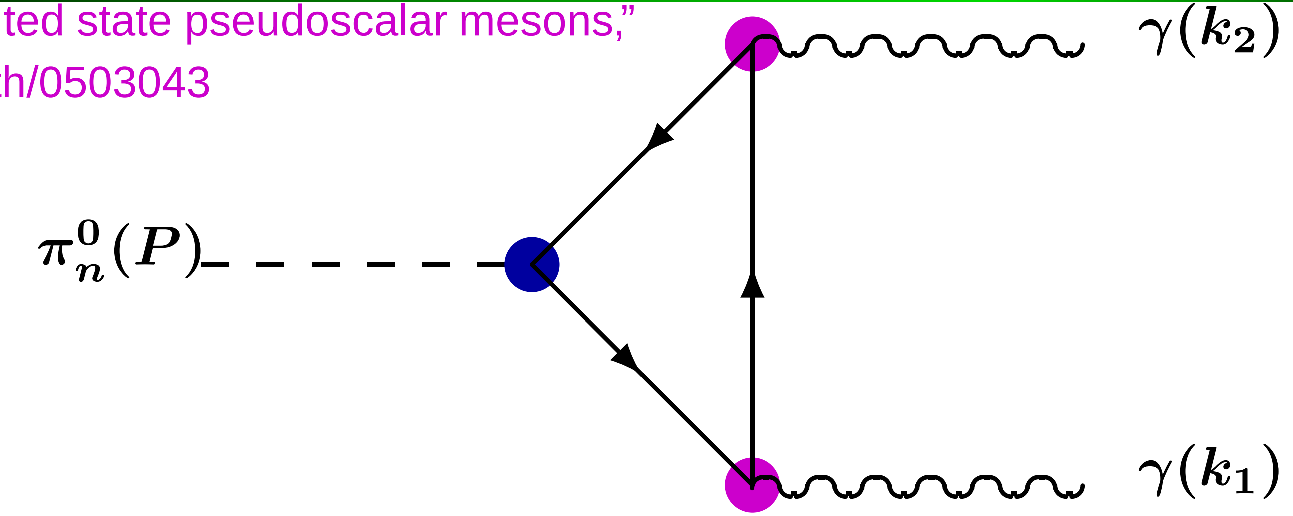


- DSE prediction
- Fascinating result: DSE and Lattice – Experimental value obtains independent of current-quark mass.
- We have understood this. Implications far-reaching.

Two-photon Couplings of Pseudoscalar Mesons

Höll, Krassnigg, Maris, *et al.*, "Electromagnetic properties of ground and excited state pseudoscalar mesons," nu-th/0503043



$$T_{\mu\nu}^{\pi_n^0}(k_1,k_2) = \frac{\alpha}{\pi} i\varepsilon_{\mu\nu\rho\sigma} k_{1\rho} k_{2\sigma}\, G^{\pi_n^0}(k_1,k_2)$$

- Define: $\mathcal{T}_{\pi_n^0}(P^2,Q^2) = G^{\pi_n^0}(k_1,k_2)\Big|_{k_1^2=Q^2=k_2^2}$

  This is a transition form factor.

- Physical Processes described by couplings:

  $g_{\pi_0^0\gamma\gamma} := \mathcal{T}_{\pi_0^0}(-m^2_{\pi_0^0}, 0)$

  Width: $\Gamma_{\pi_n^0\gamma\gamma} = \alpha_{\rm em}^2 \,\dfrac{m_{\pi_n}^3}{16\pi^3}\, g^2_{\pi_n\gamma\gamma}$

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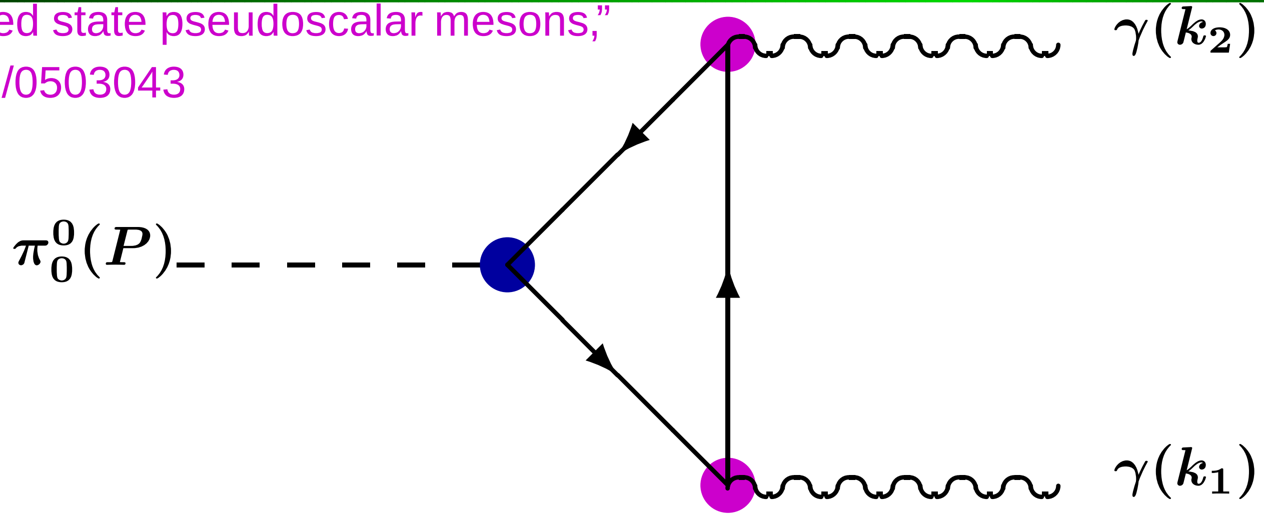
Two-photon Couplings: Goldstone Mode

Höll, Krassnigg, Maris, *et al.*,
"Electromagnetic properties of ground and excited state pseudoscalar mesons,"
nu-th/0503043



- $$T_{\mu\nu}^{\pi_0^0}(k_1,k_2) = \frac{\alpha}{\pi} i\varepsilon_{\mu\nu\rho\sigma} k_{1\rho} k_{2\sigma}\, G^{\pi_0^0}(k_1,k_2)$$

- Chiral limit, model-independent and algebraic result

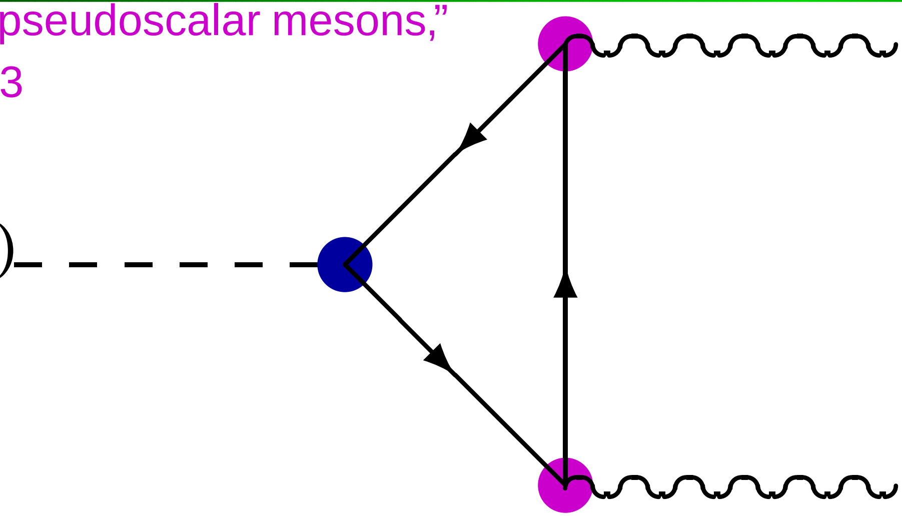
  $$g_{\pi_0^0\gamma\gamma} := \mathcal{T}_{\pi_0^0}(-m_{\pi_0^0}^2 = 0, 0) = \frac{1}{2}\frac{1}{f_{\pi_0}}$$

  So long as truncation veraciously preserves chiral symmetry and the pattern of its dynamical breakdown

- The most widely known consequence of the Abelian anomaly

Two-photon Couplings: Transition Form Factor

Höll, Krassnigg, Maris, *et al.*, "Electromagnetic properties of ground and excited state pseudoscalar mesons," nu-th/0503043



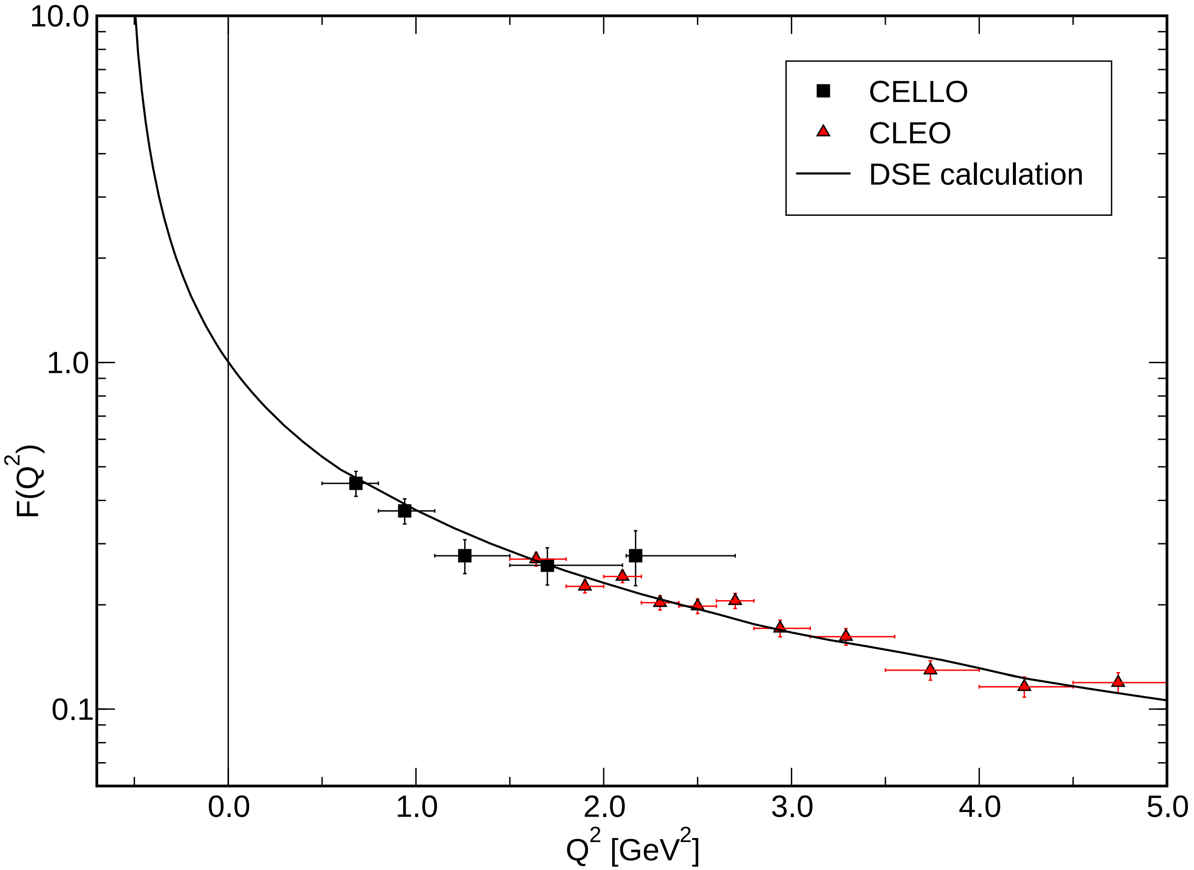
$$T^{\pi^0_n}_{\mu\nu}(k_1,k_2) = \frac{\alpha}{\pi} i\varepsilon_{\mu\nu\rho\sigma} k_{1\rho} k_{2\sigma}\, G^{\pi^0_n}(k_1,k_2)$$

So long as truncation preserves chiral symmetry and the pattern of its dynamical breakdown, and the one-loop renormalisation group properties of QCD: model-independent result – $\forall n$:

$$\mathcal{T}_{\pi^0_n}(P^2,Q^2) = G^{\pi^0_n}(k_1,k_2)\Big|_{k_1^2=Q^2=k_2^2} \stackrel{Q^2\gg\Lambda^2_{\rm QCD}}{=} \frac{4\pi^2}{3}\frac{f_{\pi_n}}{Q^2}$$

Two-photon Couplings: Transition Form Factor

Maris and Tandy, " Electromagnetic transition form-factors of light mesons," nucl-th/0201017



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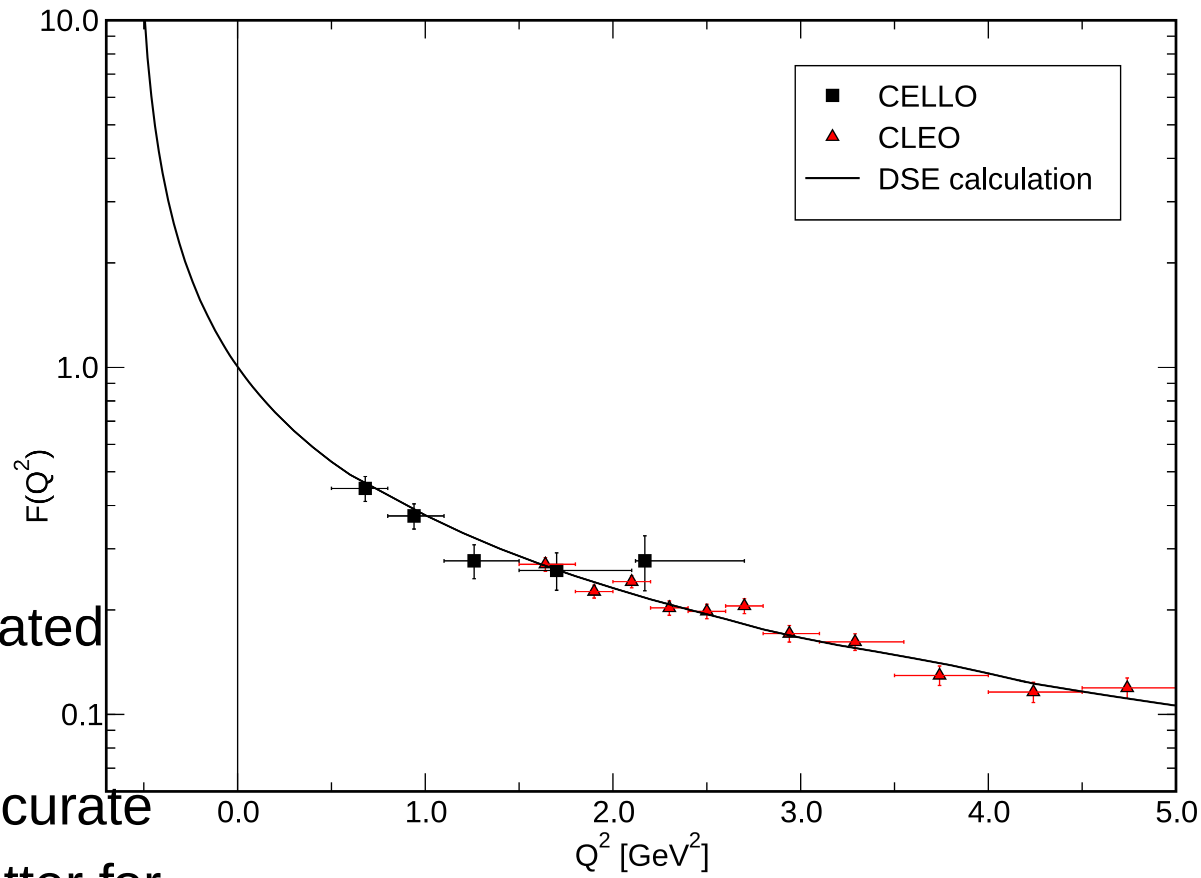

DSE result:

- normalisation calculated
- ρ-meson generated dynamically
- pQCD result accurate to $\sim$ 20% or better for $Q^2 \geq 3\,\mathrm{GeV}^2$

Transition Form Factor: Chiral limit

Höll, Krassnigg, Maris, *et al.*,
"Electromagnetic properties of ground and excited state pseudoscalar mesons,"
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- Chiral limit with DCSB: $f_{\pi_0} \neq 0$

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- Model-independent result, in chiral limit: $\forall n \geq 1$

$$\lim_{\hat{m}\to 0} \mathcal{T}_{\pi_n^0}(-m_{\pi_n}^2, Q^2) \overset{Q^2 \gg \Lambda_{\rm QCD}^2}{=} \frac{4\pi^2}{3} F_n^{(2)}(-m_{\pi_n}^2) \left.\frac{\ln^\gamma Q^2/\omega_{\pi_n}^2}{Q^4}\right|_{\hat{m}=0}$$

where:

- γ is an anomalous dimension
- ω_{π_n} is a width mass-scale

both determined, in part, by properties of the meson's Bethe-Salpeter wave function.

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where:

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  - ω_{π_n} is a width mass-scale

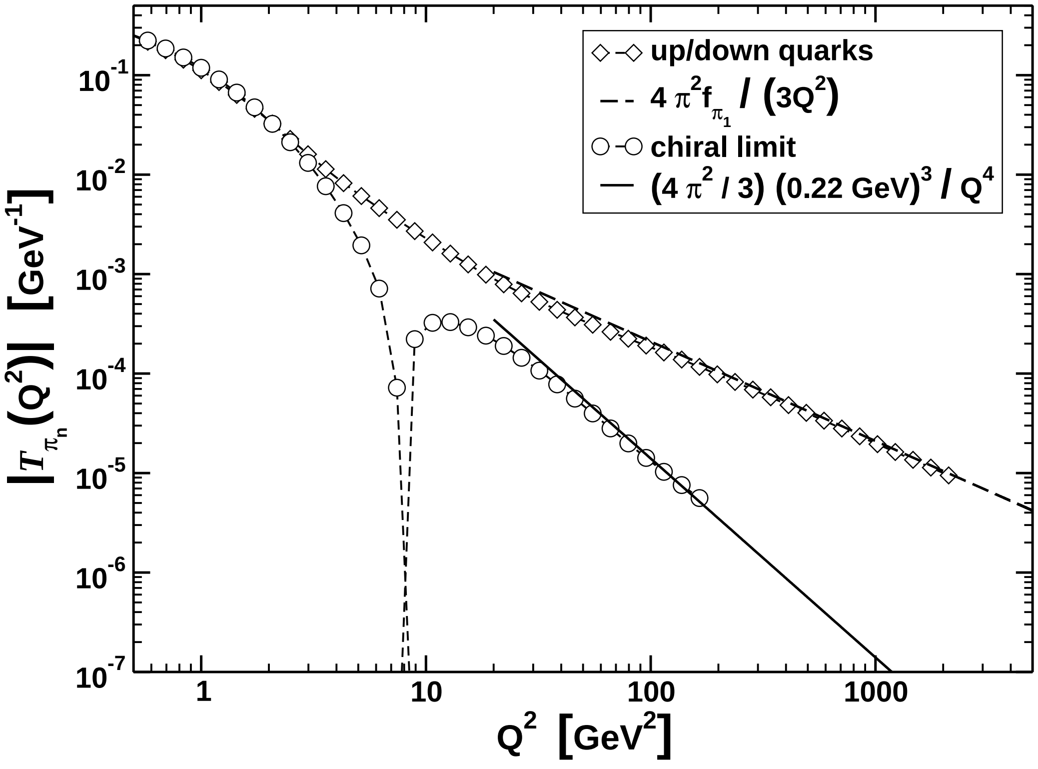
both determined, in part, by properties of the meson's Bethe-Salpeter wave function.

- Importantly, $F_n^{(2)}(-m_{\pi_n}^2) \not\propto f_{\pi_n}$. Instead, it is determined by DCSB mass-scales for π_n that do not vanish in the chiral limit.

Transition Form Factor (Chiral): RGI Rainbow-Ladder

Höll, Krassnigg, Maris, *et al*., "Electromagnetic properties of ground and excited state pseudoscalar mesons," nu-th/0503043

- $m_u(1\,\mathrm{GeV}) = m_d(1\,\mathrm{GeV}) = 0$



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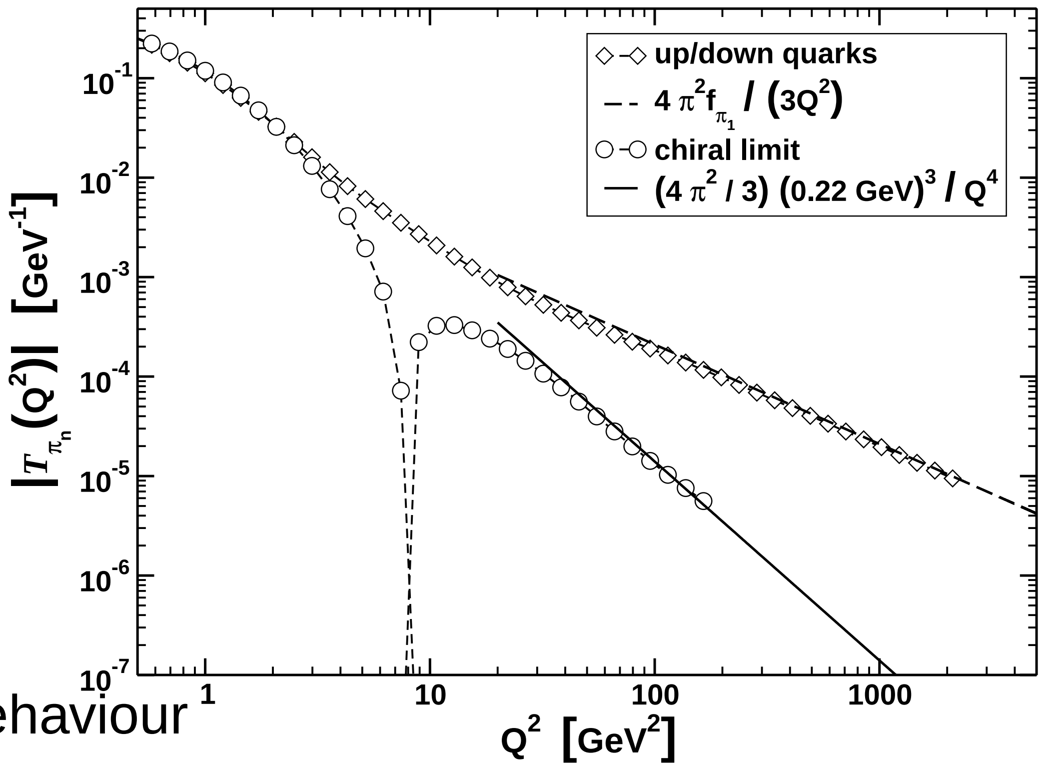

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- Again, Predicted UV-behaviour is abundantly clear
  - precise for $Q^2 > 120\,\mathrm{GeV}^2$

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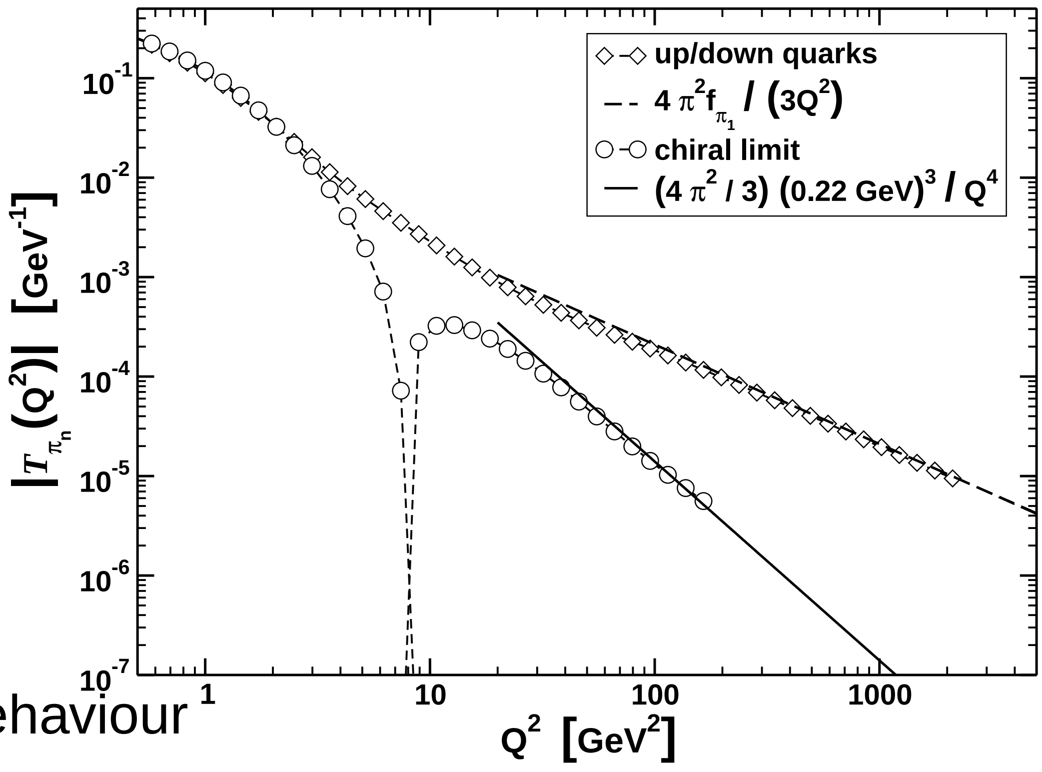
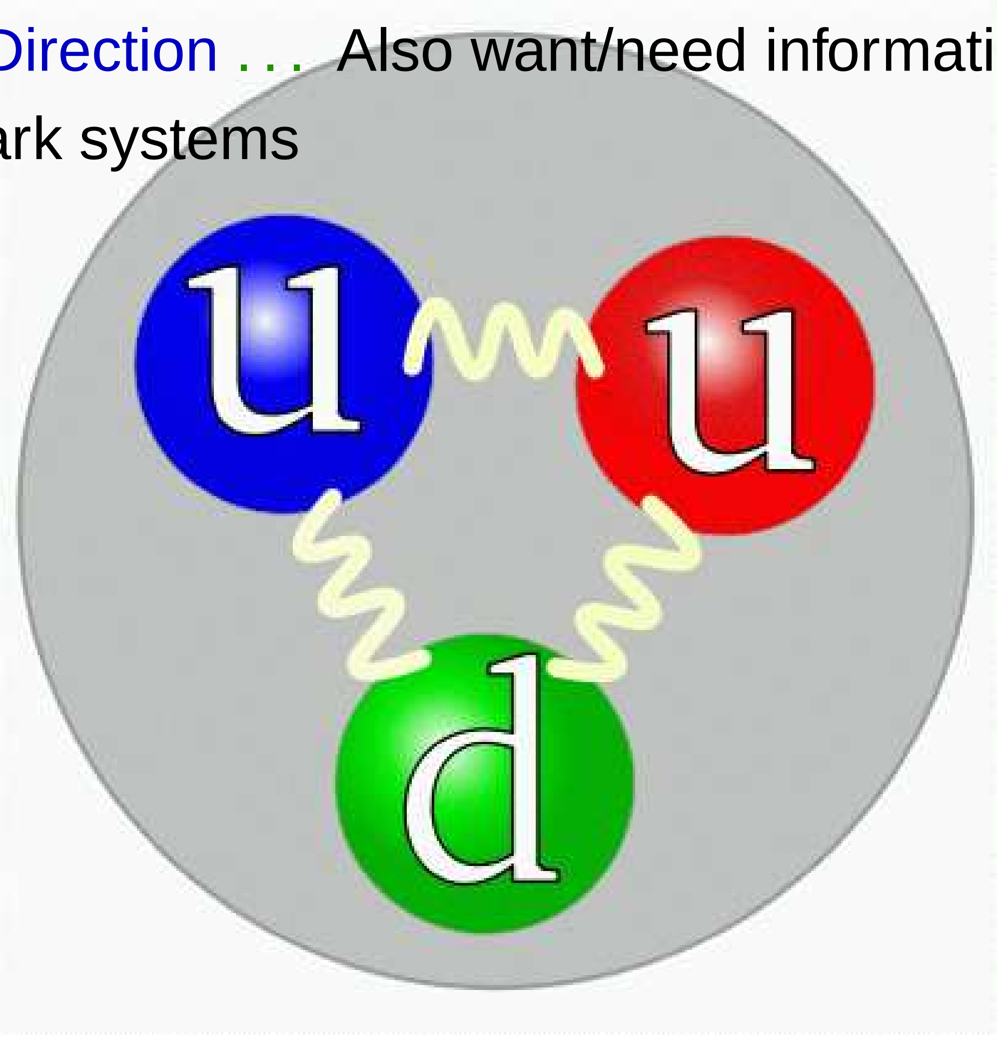


- $m_u(1\,\mathrm{GeV}) = m_d(1\,\mathrm{GeV}) = 0$
- Again, Predicted UV-behaviour is abundantly clear
  - precise for $Q^2 > 120\,\mathrm{GeV}^2$
- $$F_1^{(2)}(-m_{\pi_1}^2)\,\ln^\gamma Q^2/\omega_{\pi_1}^2\Big|_{\hat m=0} \approx (0.22\,\mathrm{GeV})^3 \simeq -\langle\bar q q\rangle^0 \quad (3)$$

Nucleon Challenge

Nucleon Challenge

- Another Direction . . . Also want/need information about three-quark systems



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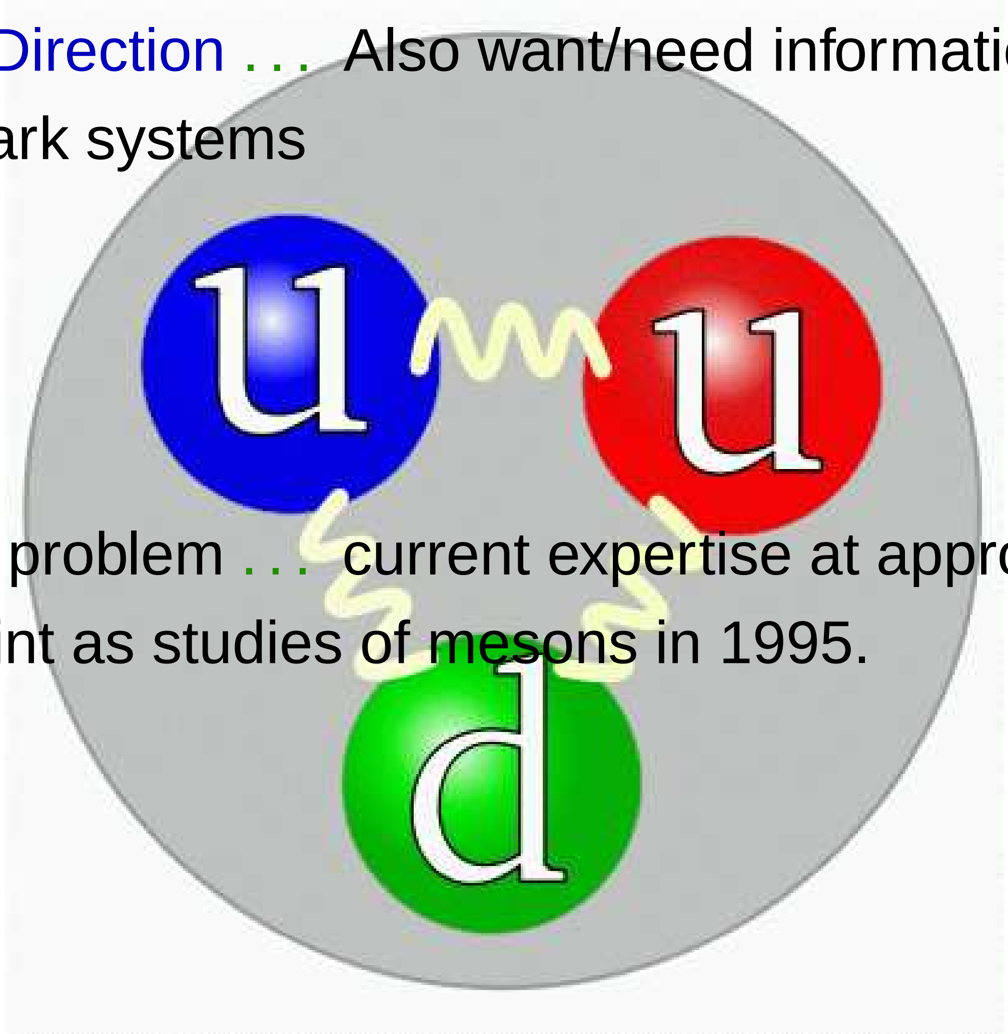

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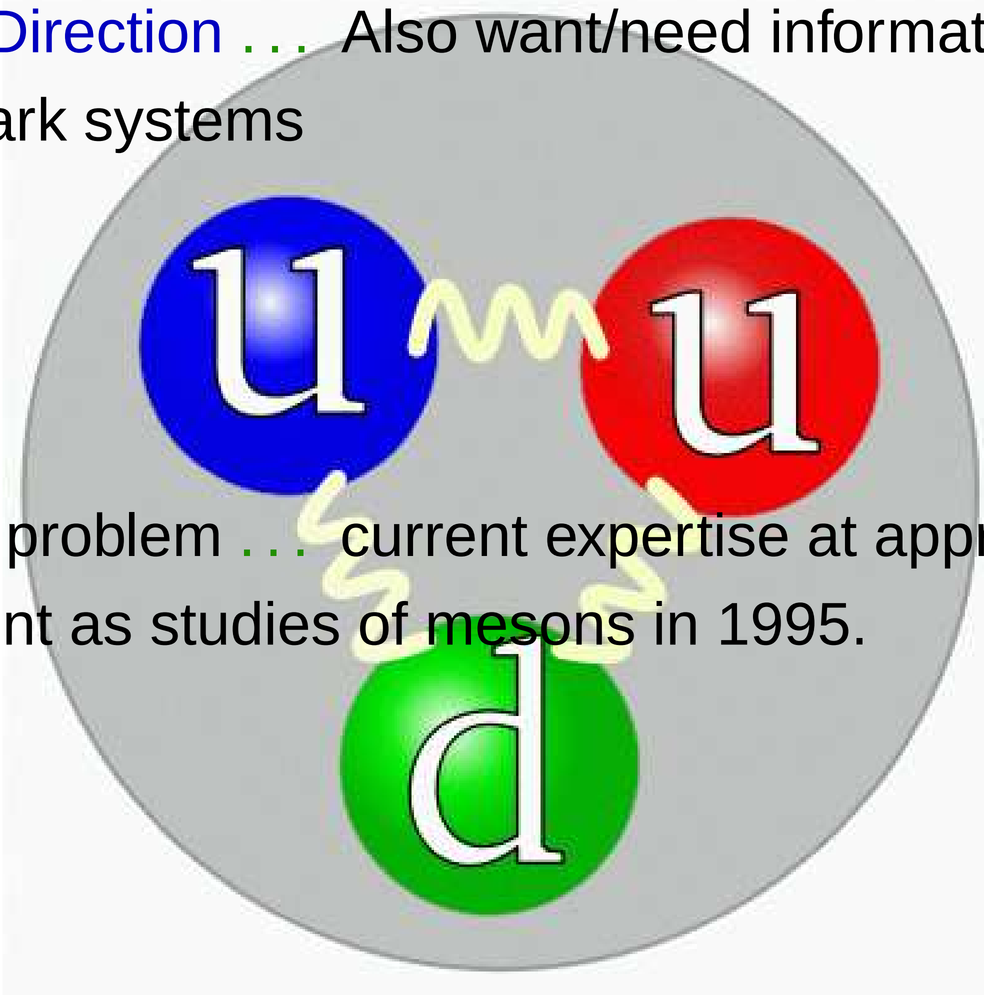

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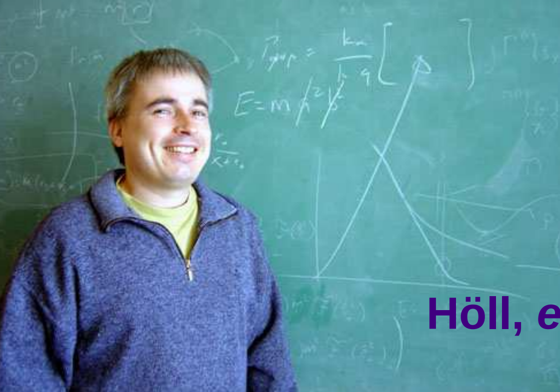
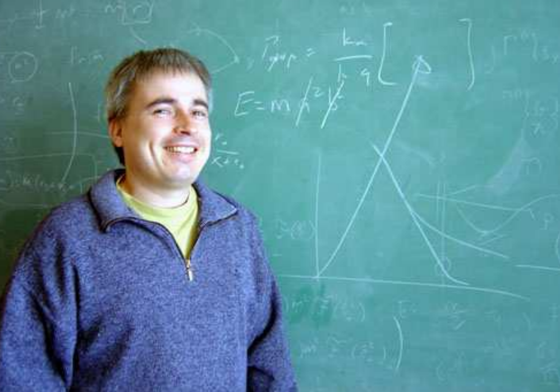
- Namely . . . Model-building and Phenomenology, constrained by the DSE results outlined already.



Nucleon EM Form Factors: A Précis

Höll, *et al.*: nu-th/0412046 & nu-th/0501033



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(Oettel, Hellstern, Alkofer, Reinhardt: nucl-th/9805054)

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- Critical to anticipate pion cloud effects
  Roberts, Tandy, Thomas, *et al.*, nu-th/02010084

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Faddeev equation

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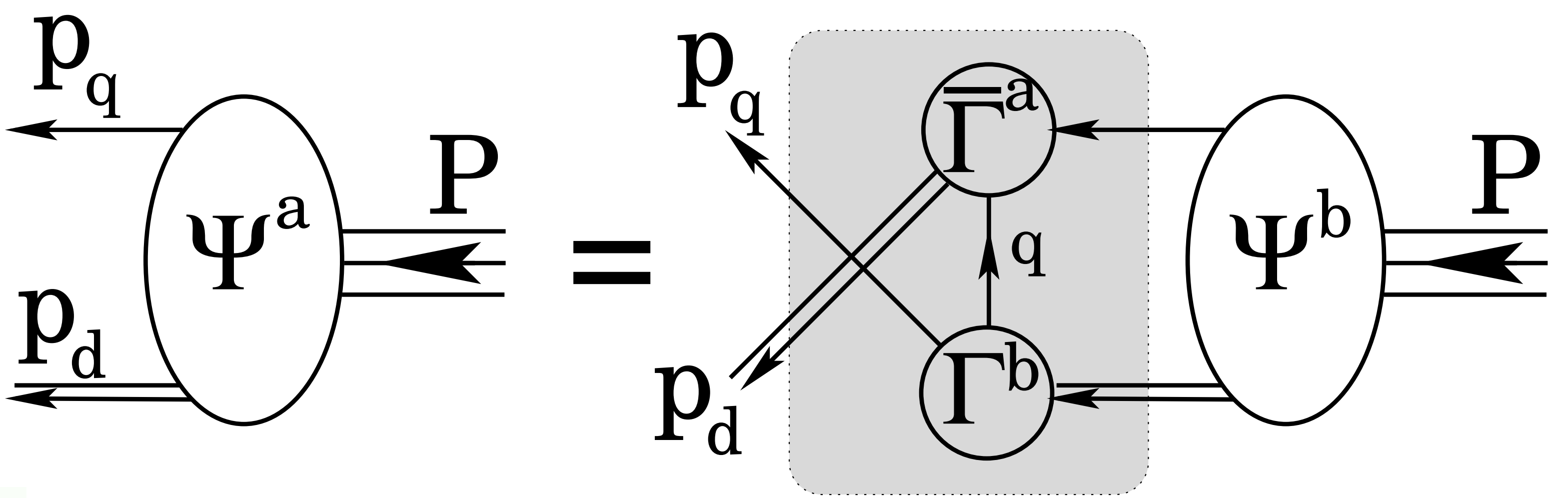

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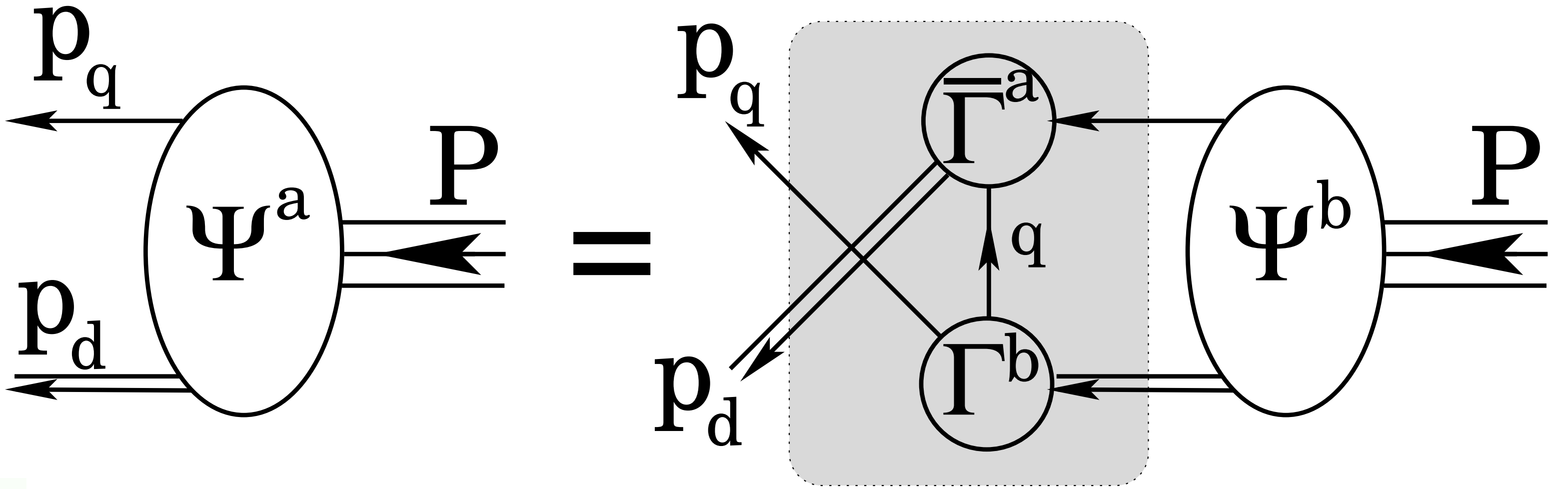
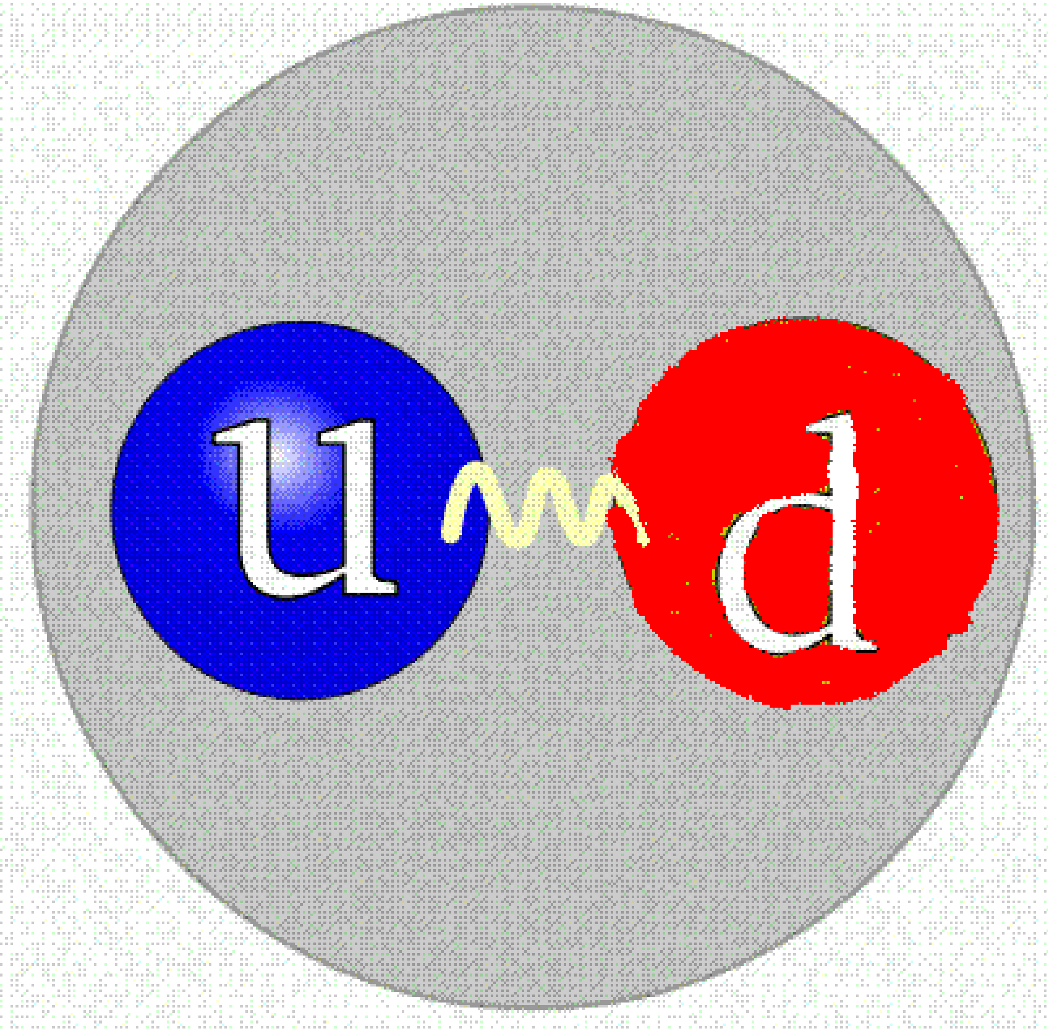


- Linear, Homogeneous Matrix equation
  - Yields *wave function* (Poincaré Covariant Faddeev Amplitude) that describes quark-diquark relative motion within the nucleon
- Scalar and Axial-Vector Diquarks ... In Nucleon's Rest Frame Amplitude has ... $s-$, $p-$ & $d-$wave correlations

Diquark correlations



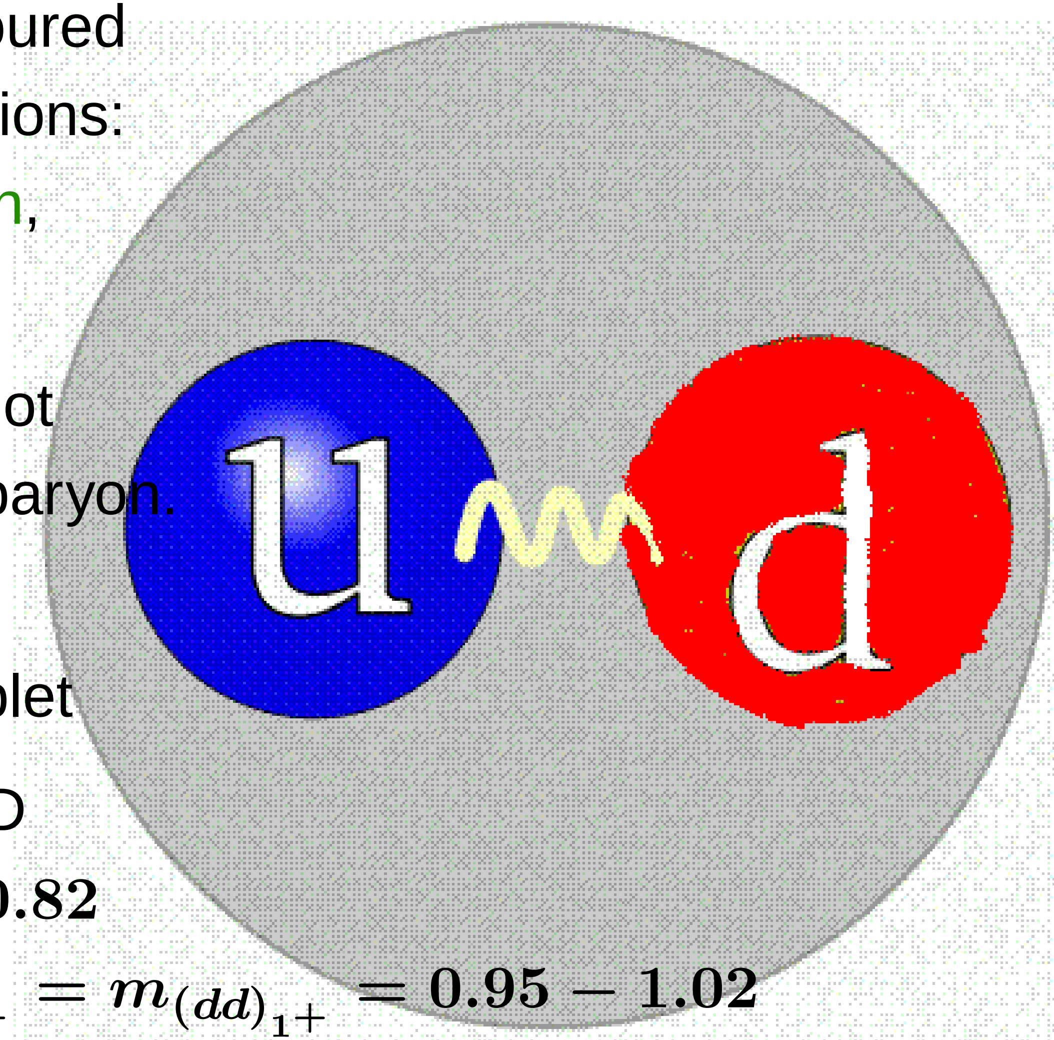
QUARK-QUARK

Diquark correlations

- Same interaction that describes mesons also generates three coloured quark-quark correlations: blue–red, blue–green, green–red
- Confined … Does not escape from within baryon.
- Scalar is isosinglet, Axial-vector is isotriplet
- DSE and lattice-QCD

$$m_{[ud]_{0^+}} = 0.74 - 0.82$$

$$m_{(uu)_{1^+}} = m_{(ud)_{1^+}} = m_{(dd)_{1^+}} = 0.95 - 1.02$$



QUARK-QUARK

Nucleon-Photon Vertex

M. Oettel, M. Pichowsky
and L. von Smekal, nu-th/9909082

Nucleon-Photon Vertex

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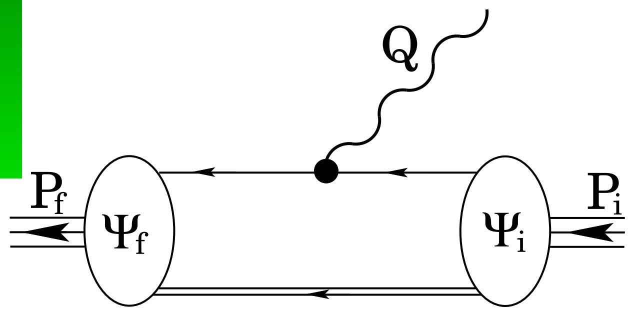
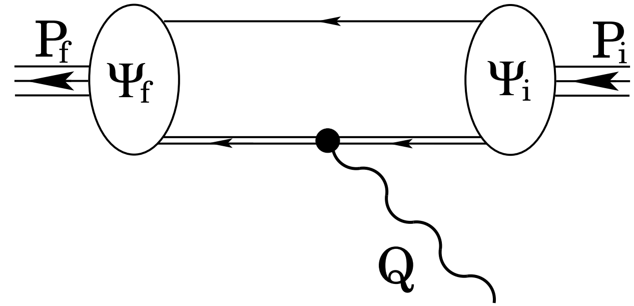
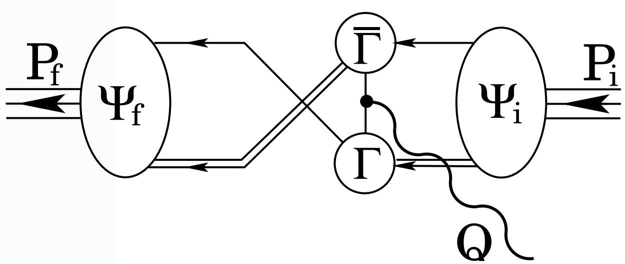
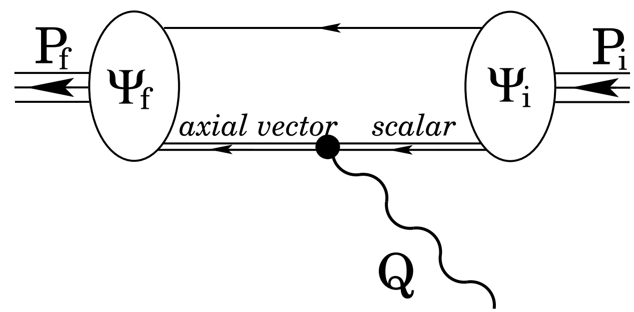
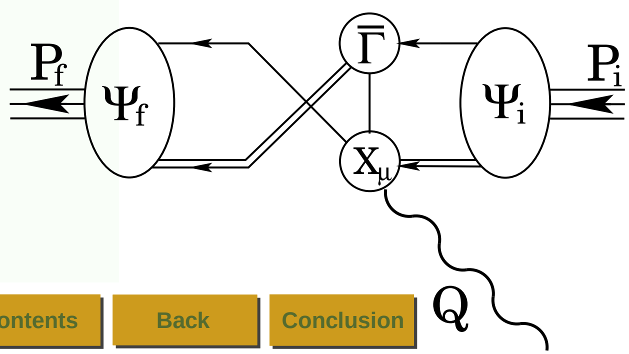
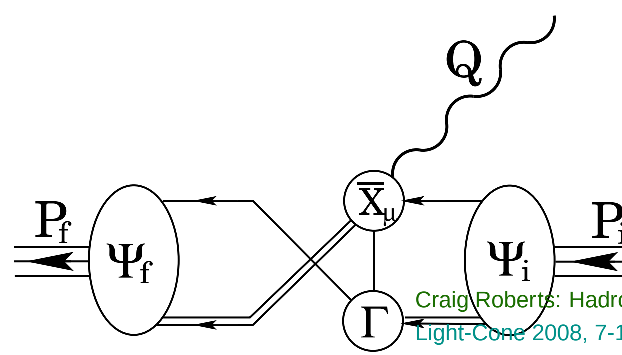




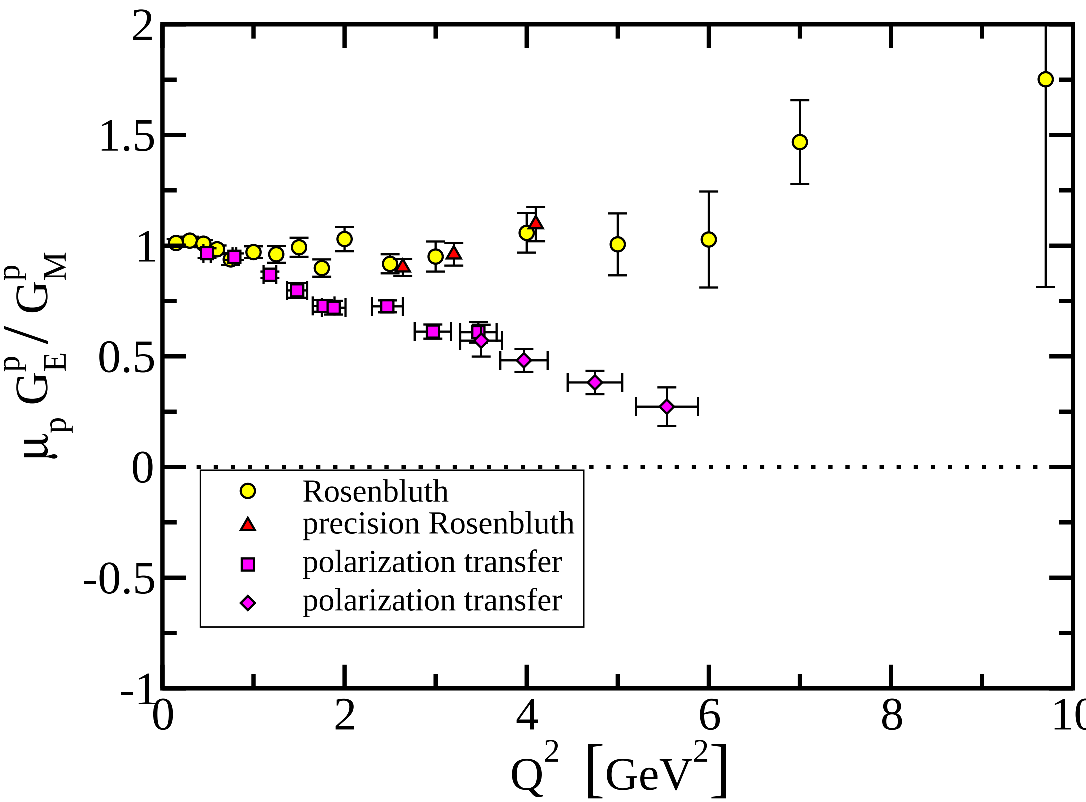








Form Factor Ratio: GE/GM



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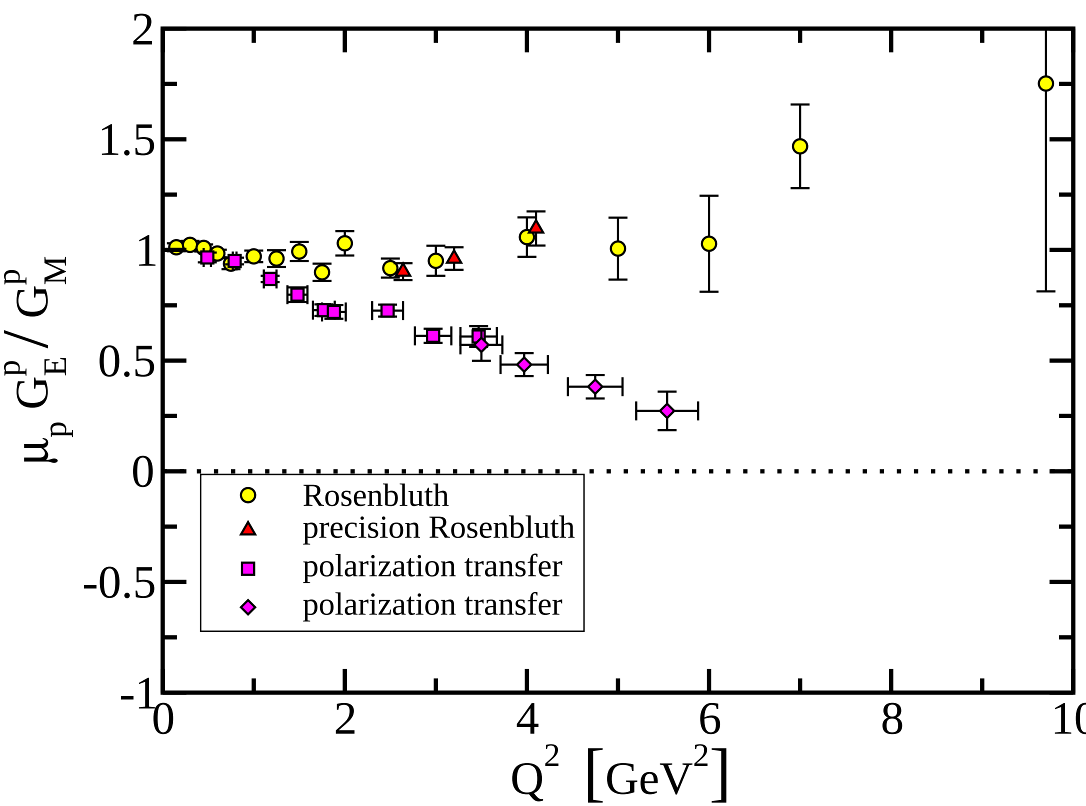

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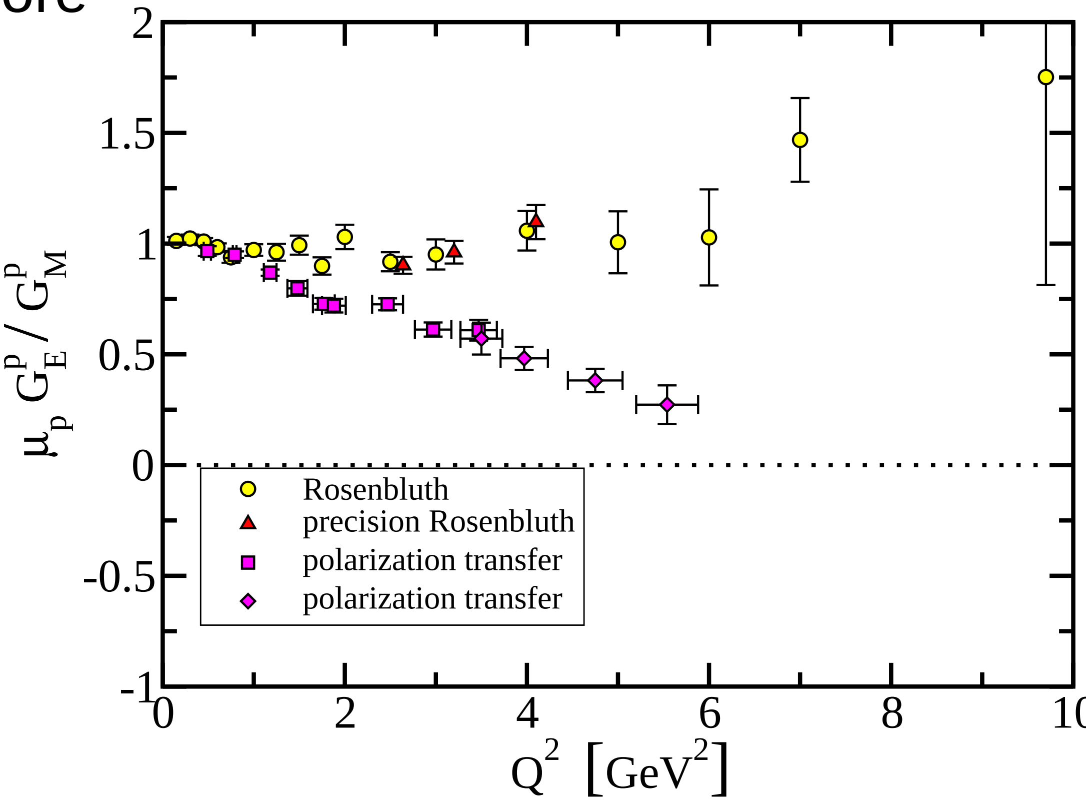

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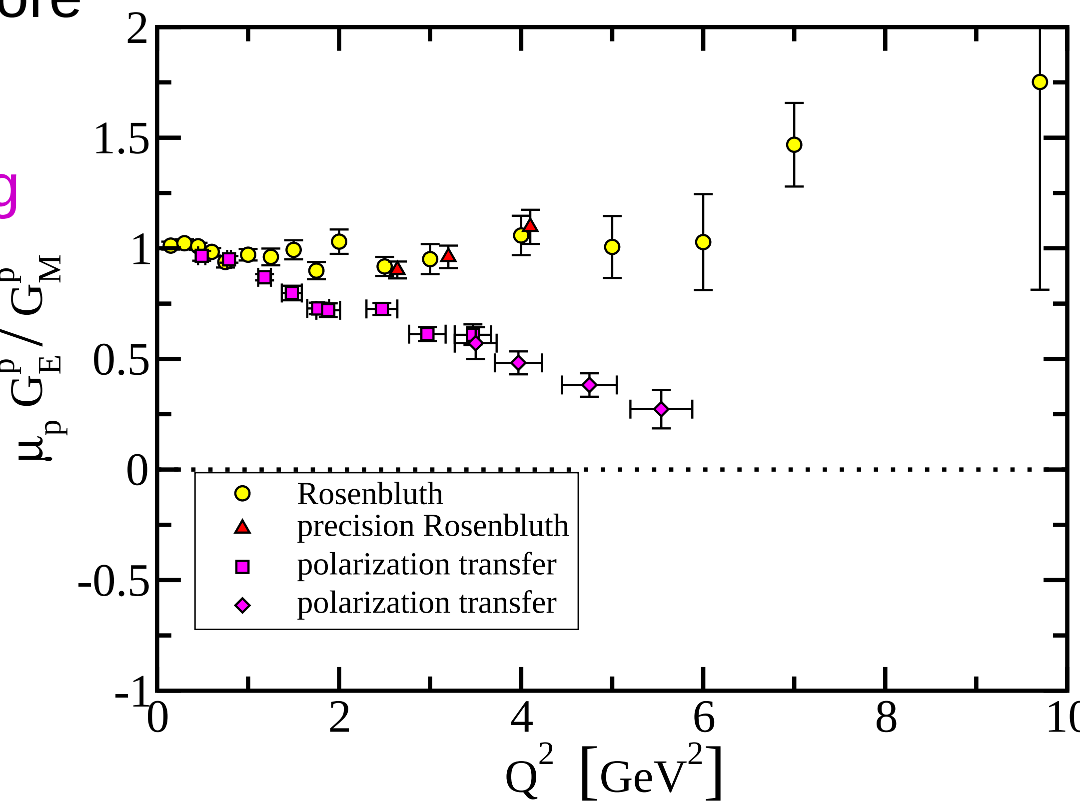

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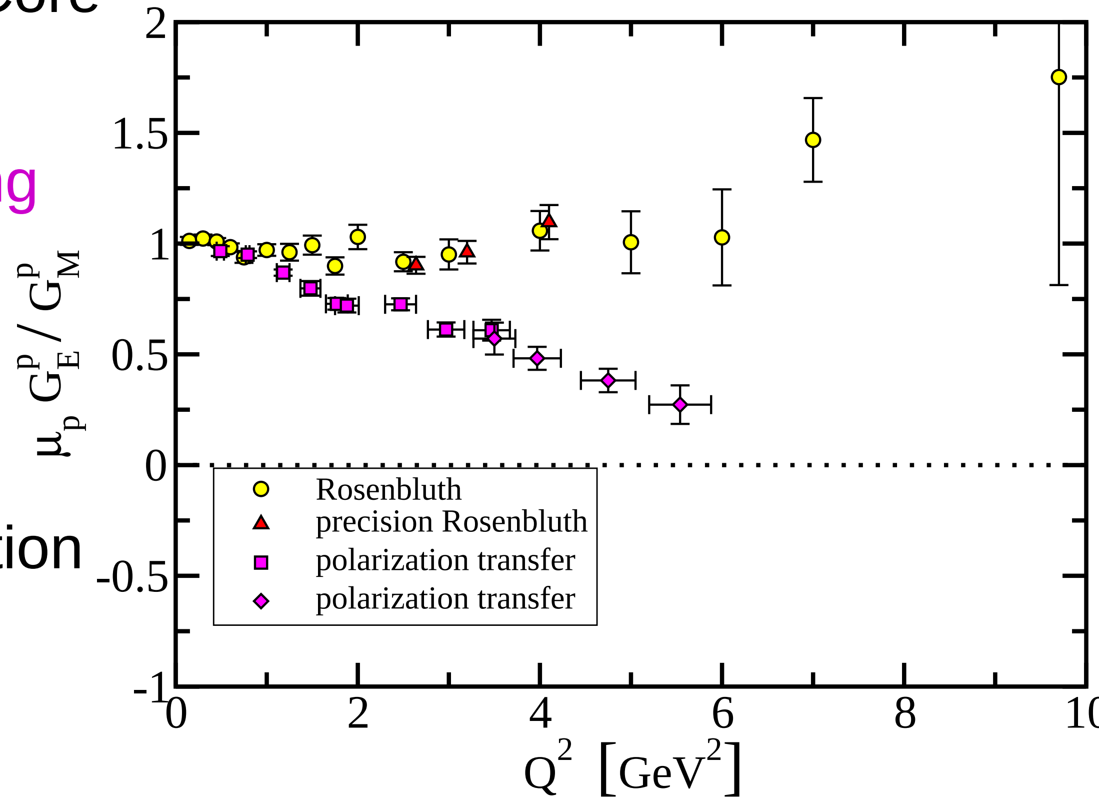

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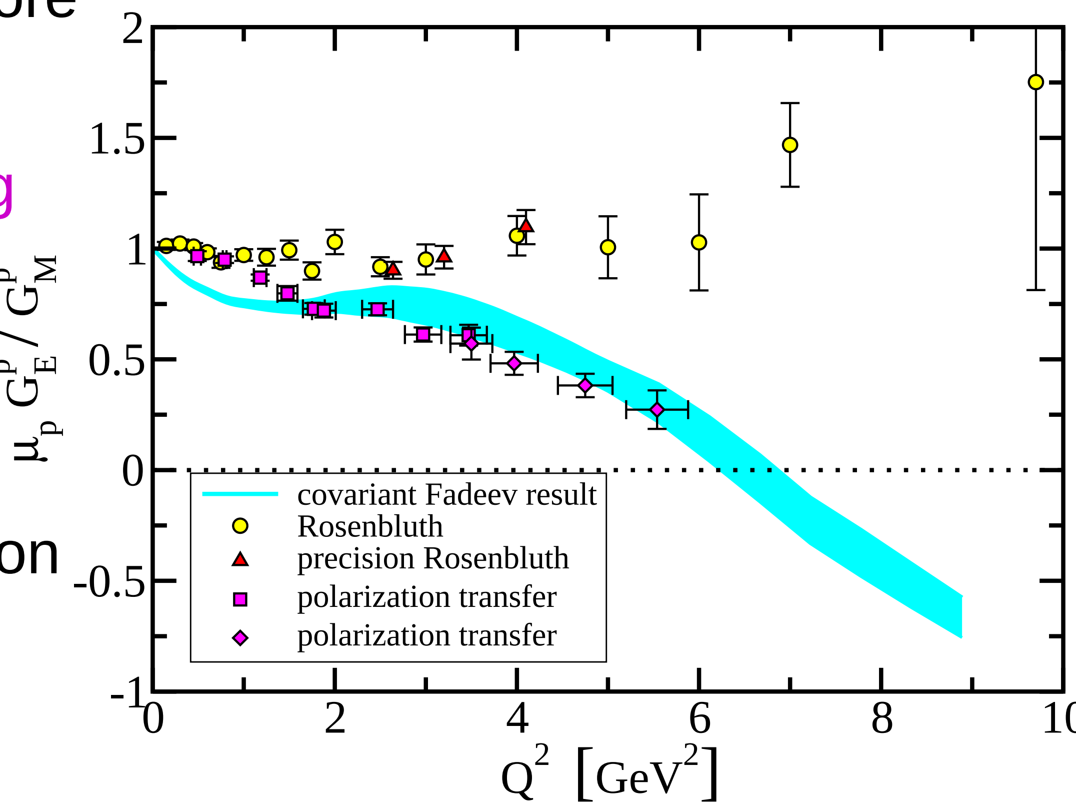

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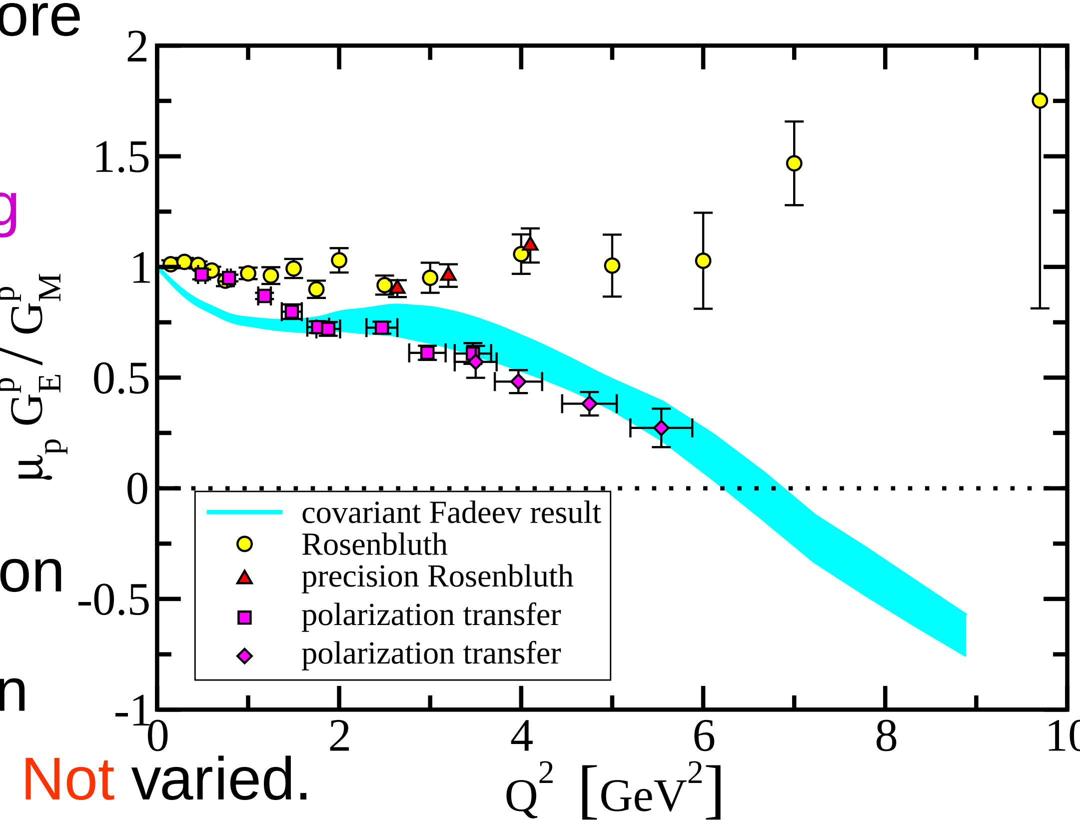

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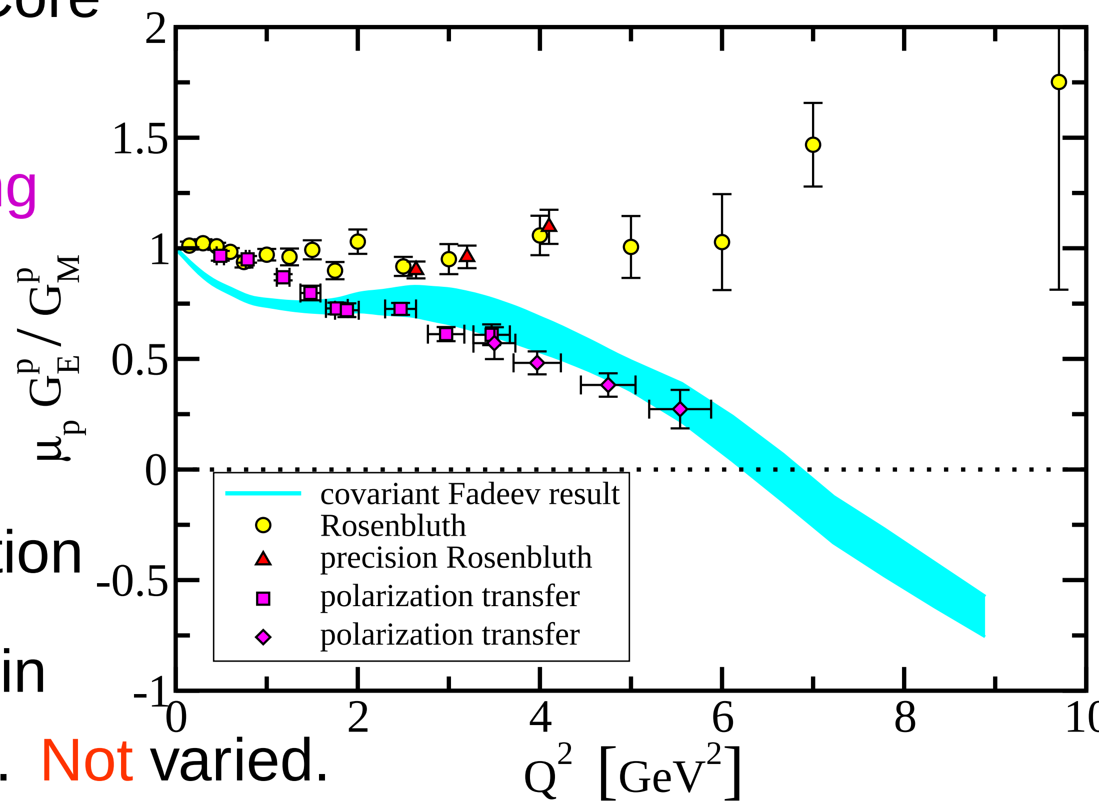

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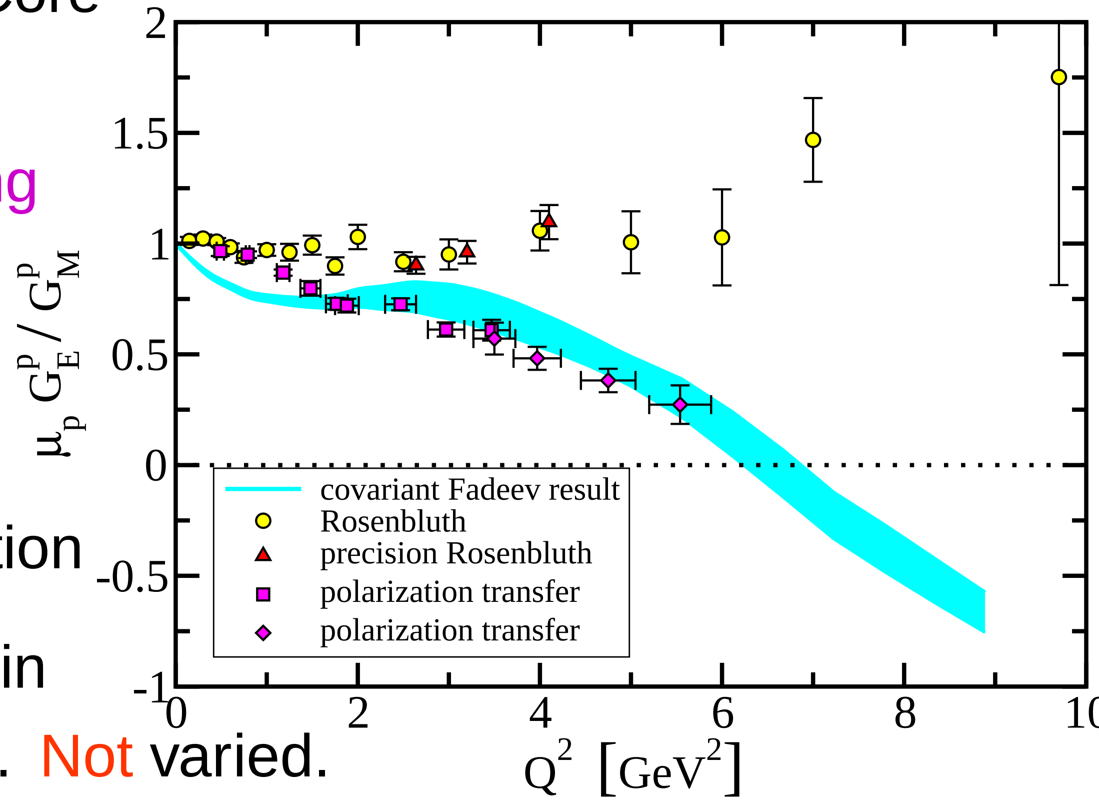

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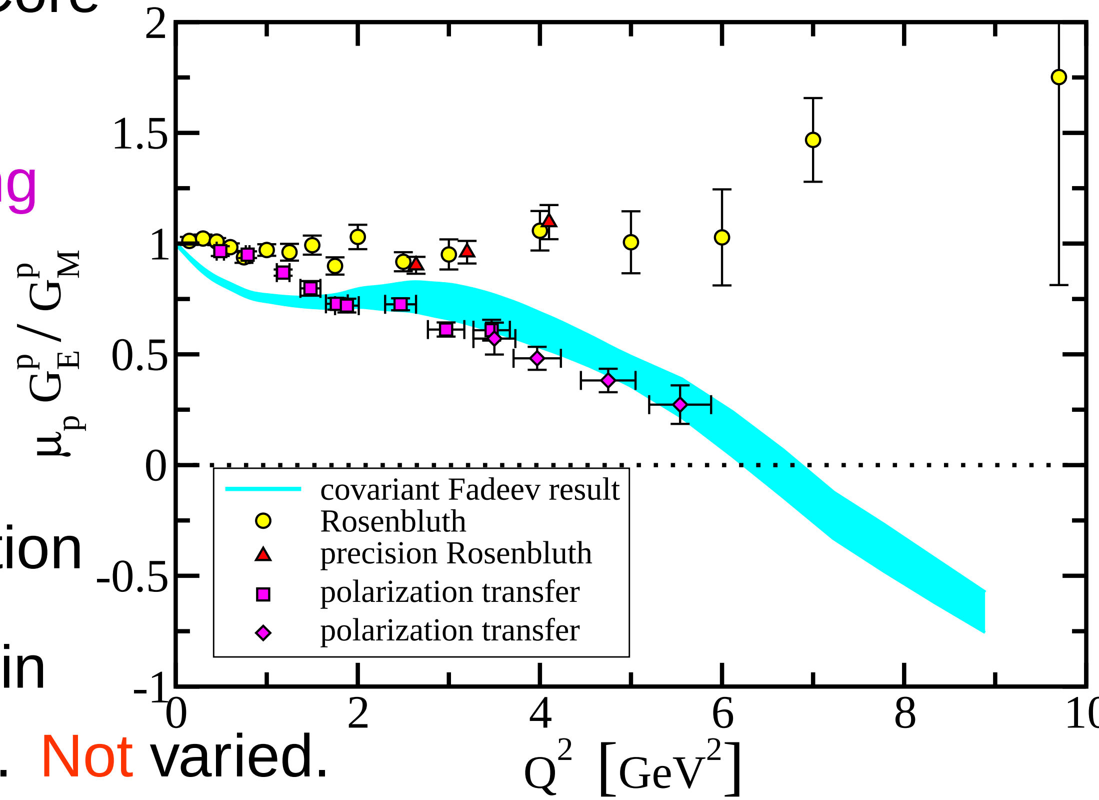

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Hall-A Neutron FF

- Preliminary result

  E02-013 - Wojtsekhowski & Cates & Liyanage

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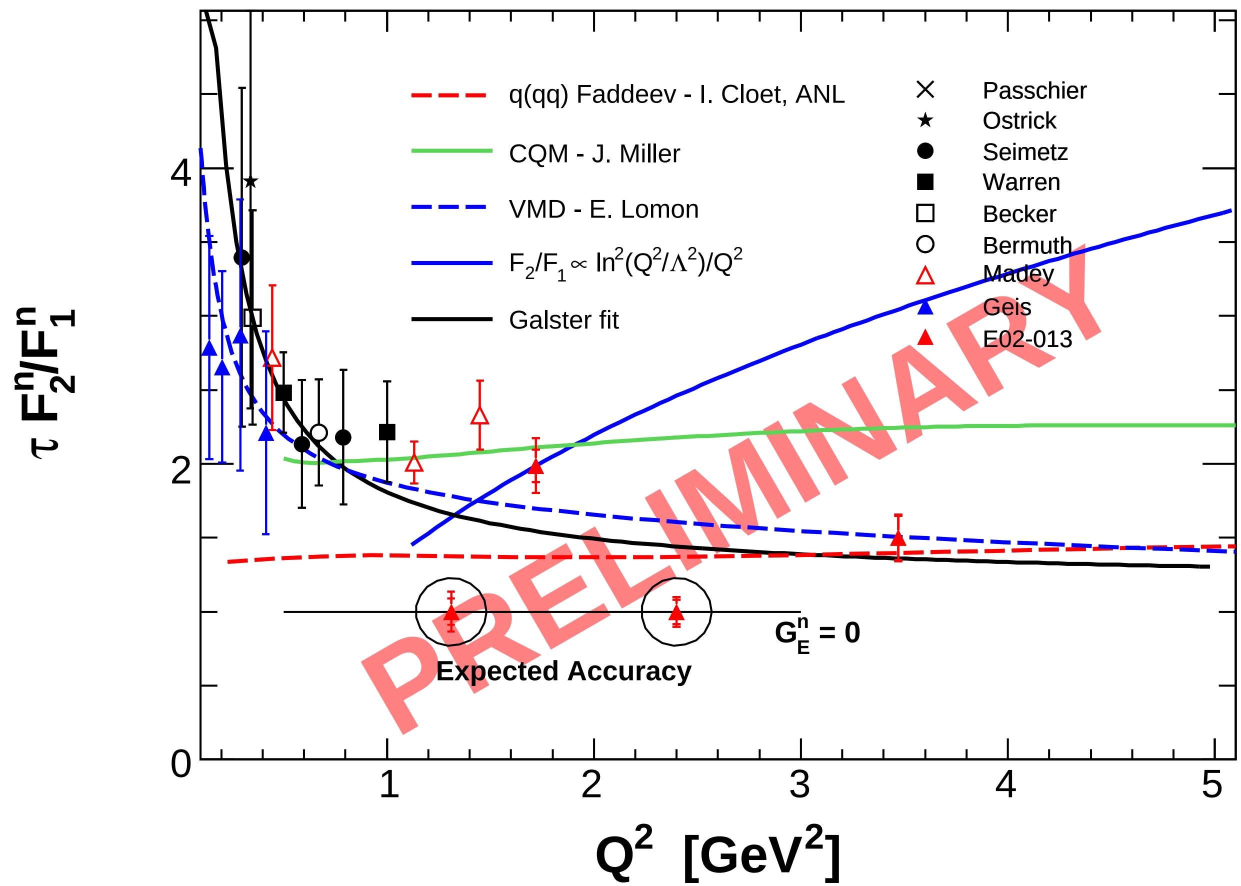

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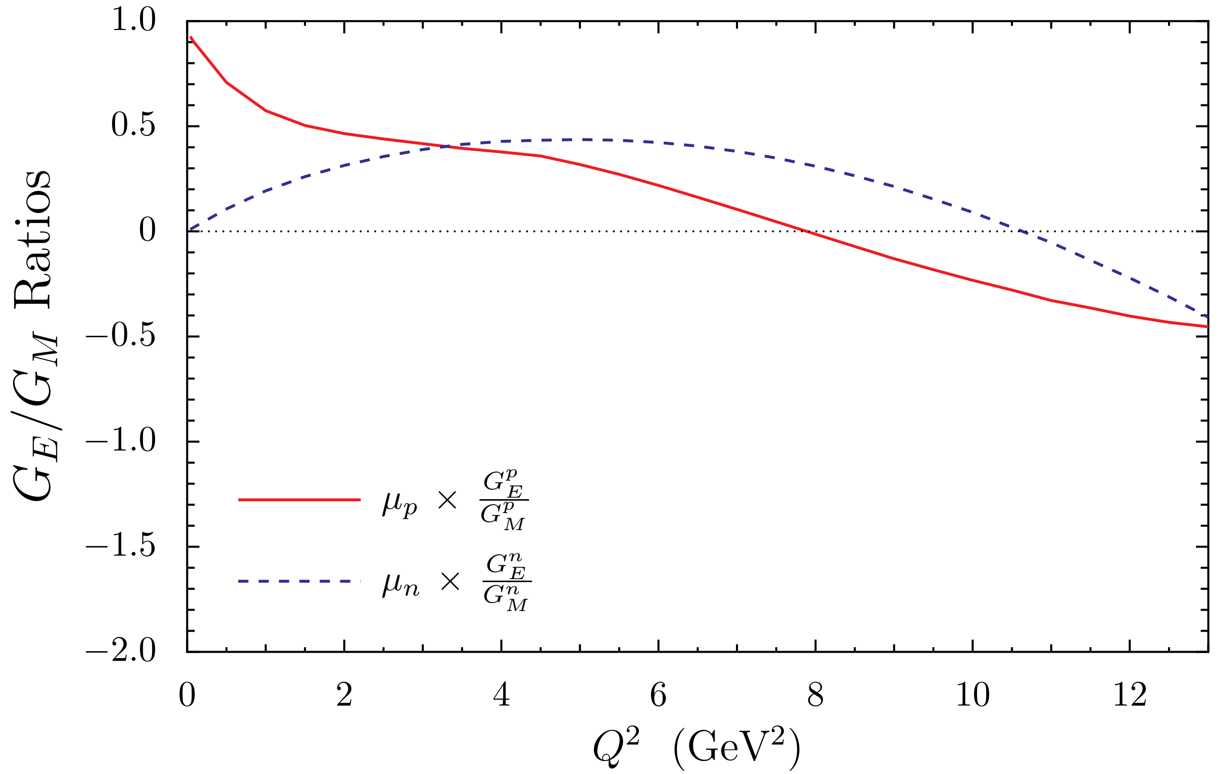

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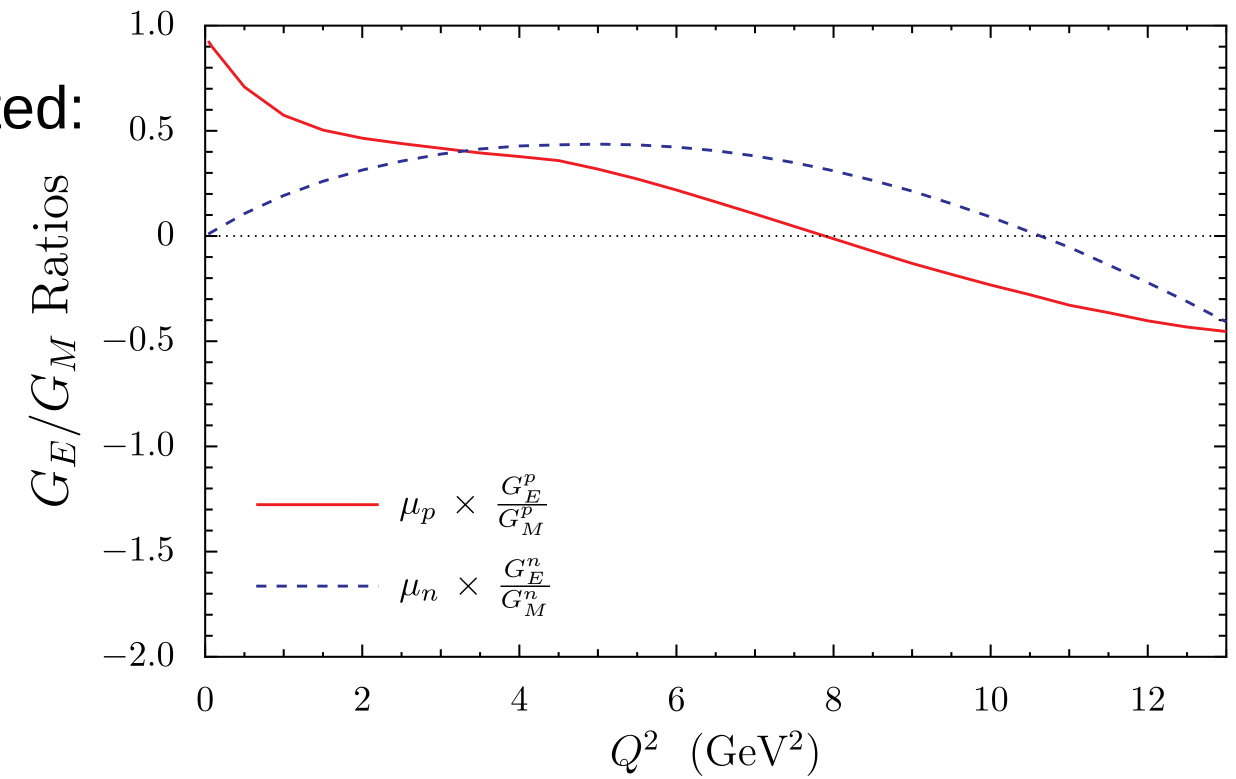

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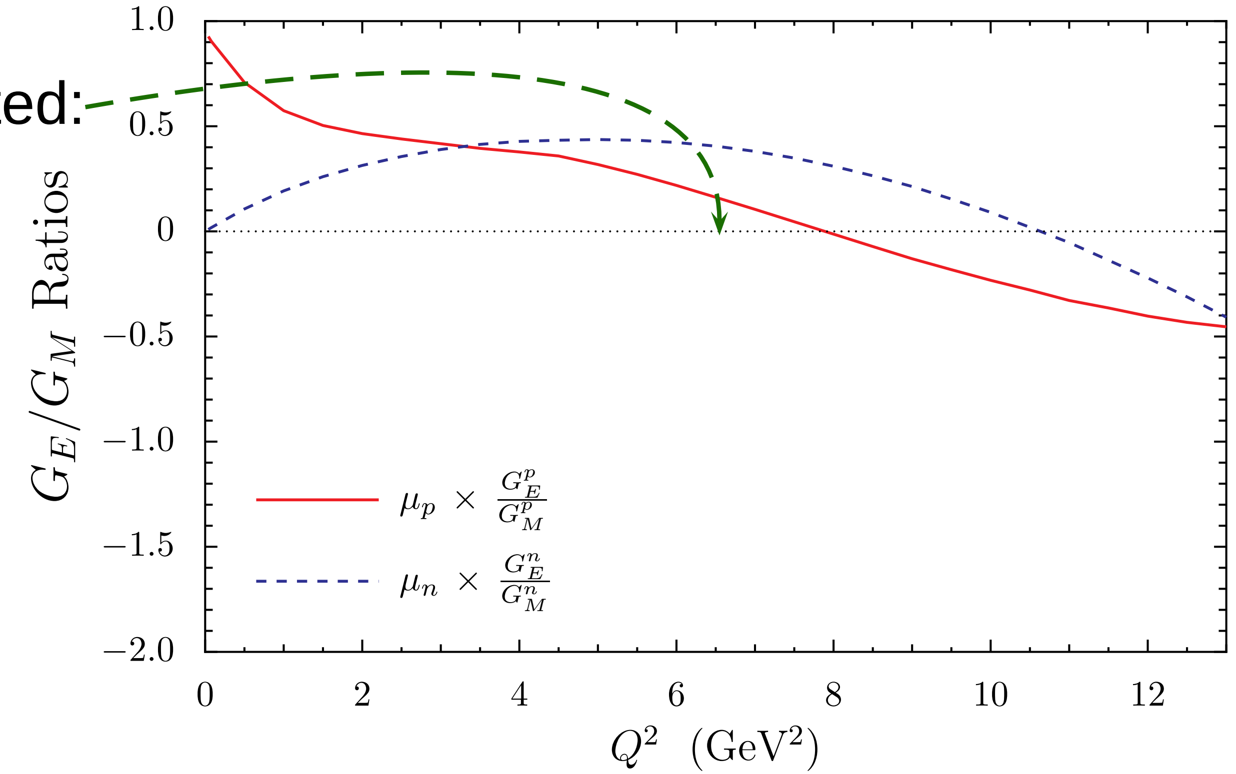

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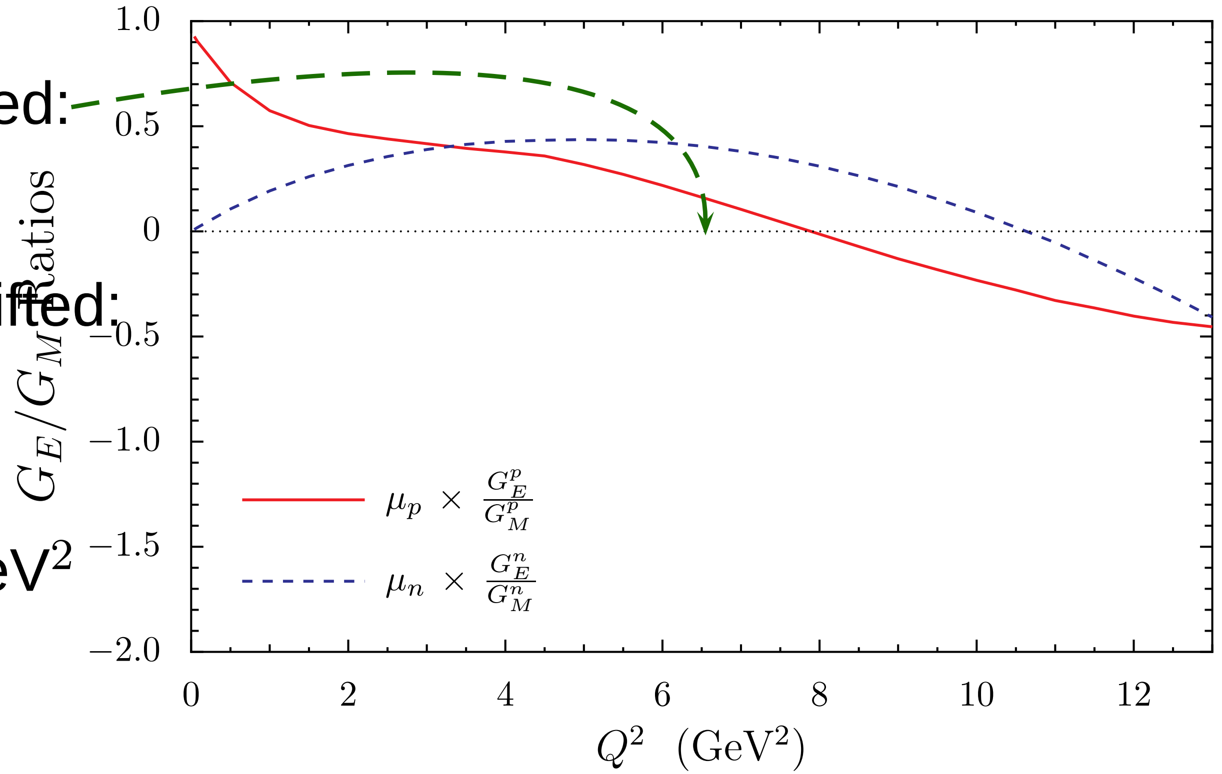

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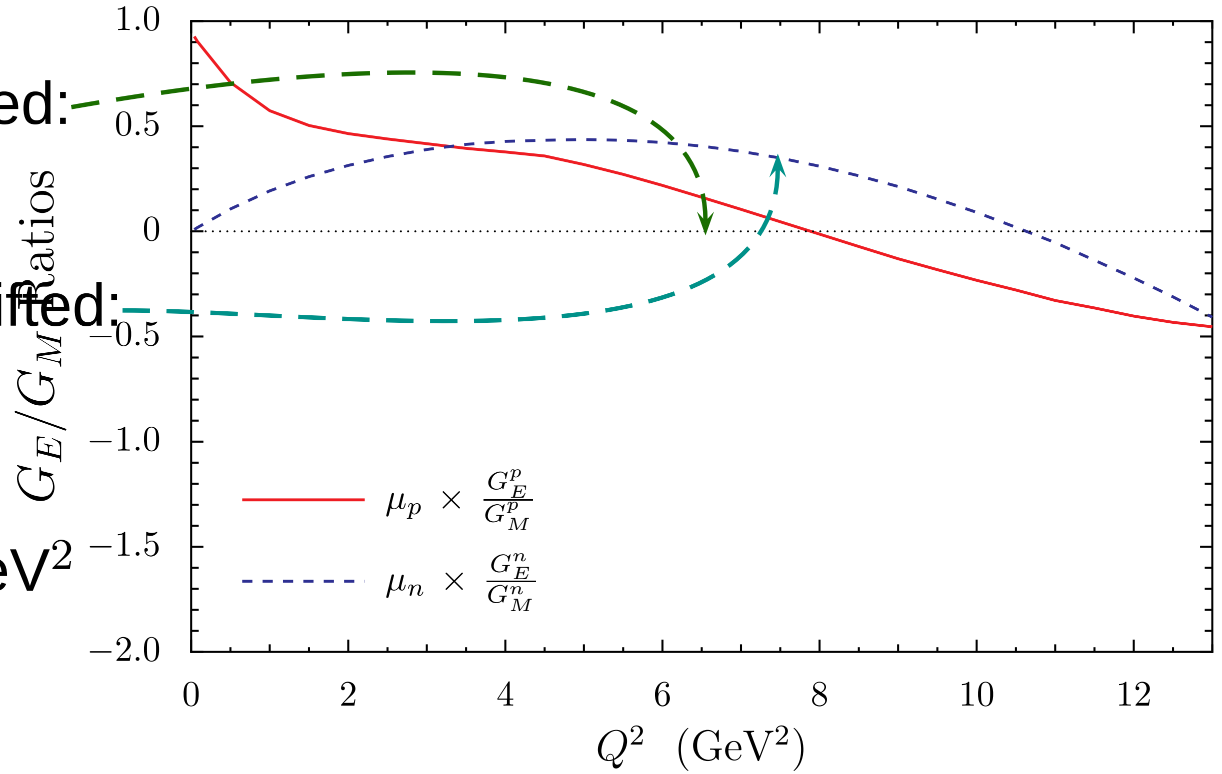

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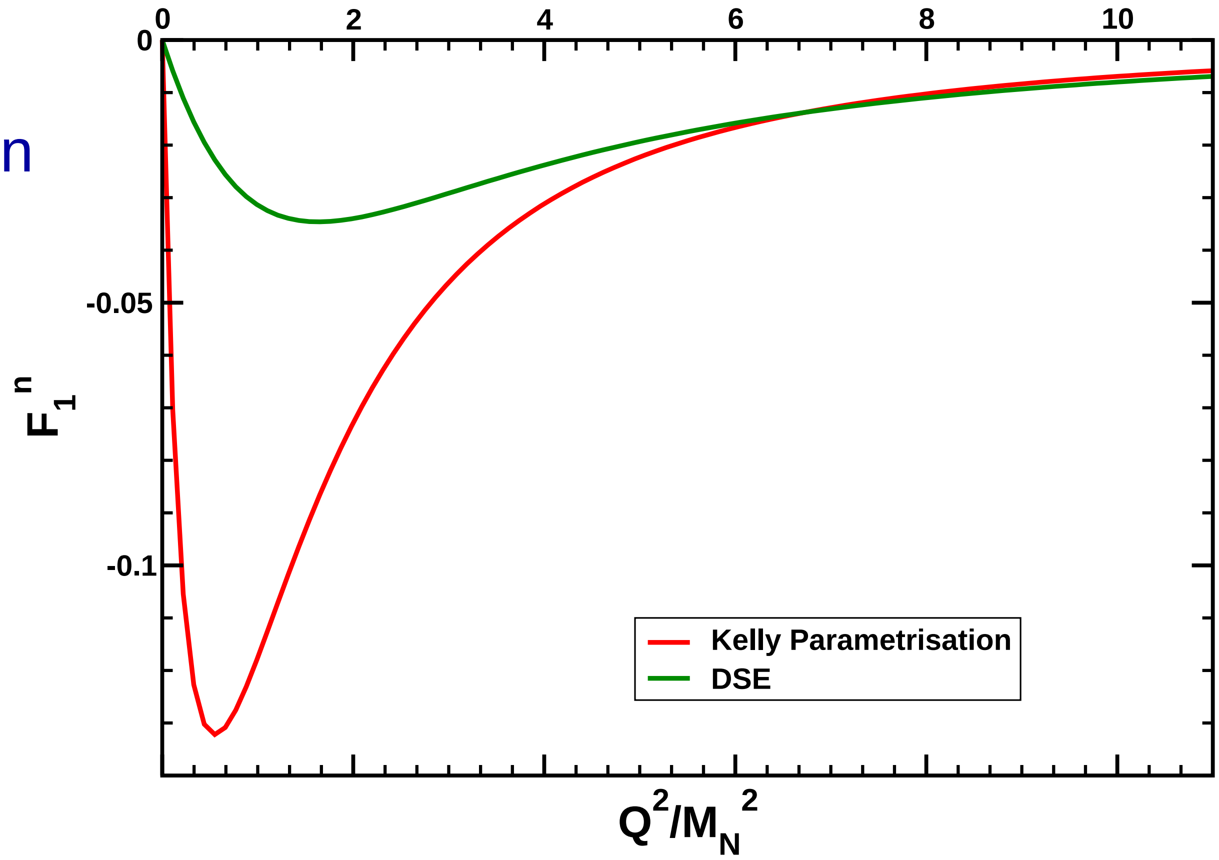

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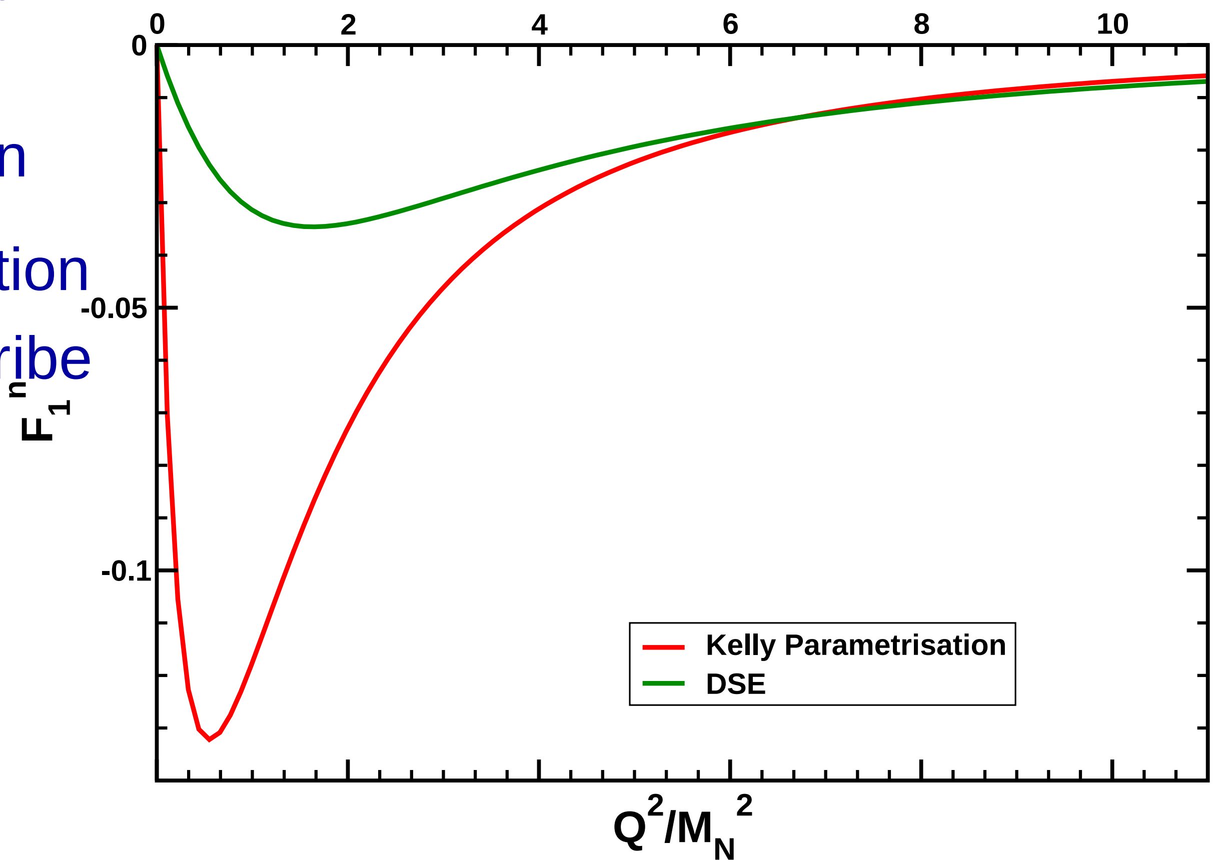

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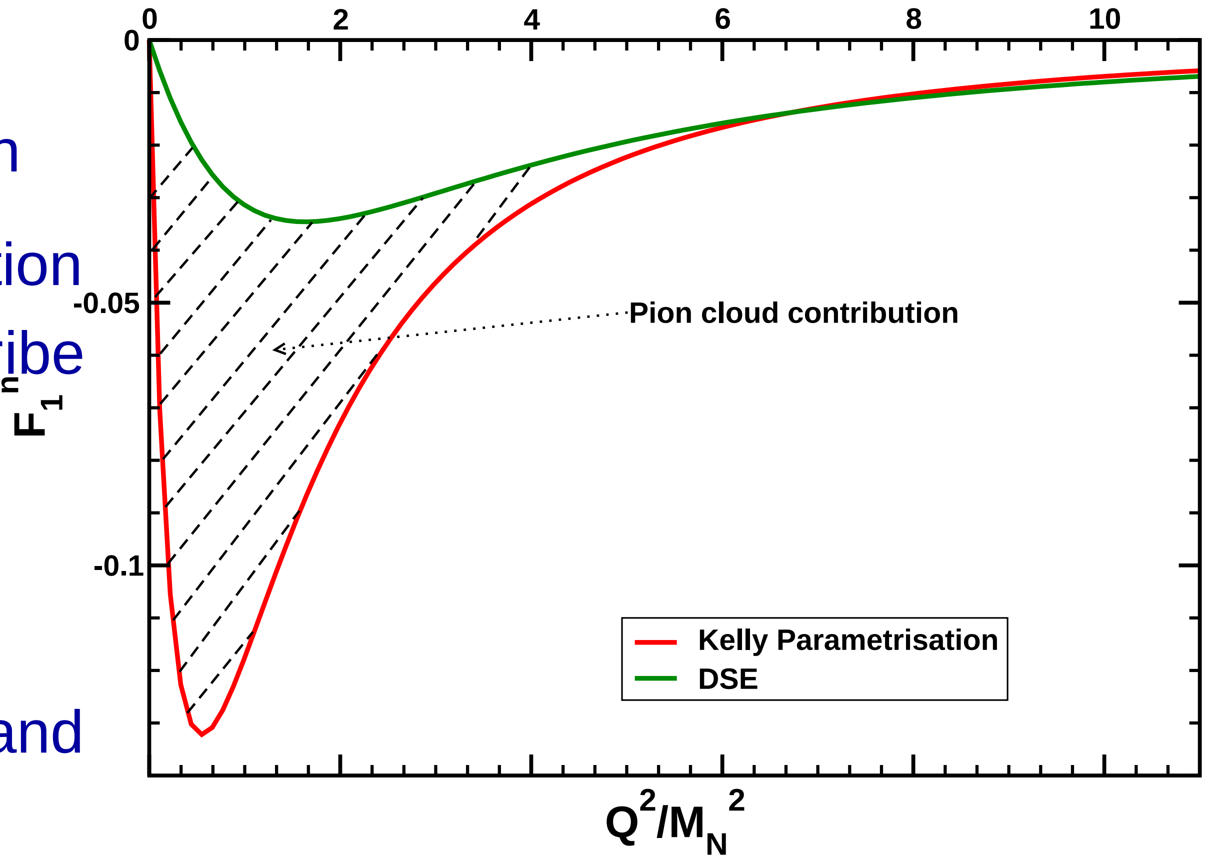

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        – Generation of fermion mass from *nothing*
      - Quark & Gluon Confinement
        – Coloured objects not detected, not detectable?
- $\Rightarrow$ Understanding InfraRed (long-range)
  .... behaviour of $\alpha_s(Q^2)$

Dyson-Schwinger Equations

- Well suited to Relativistic Quantum Field Theory
- Simplest level: Generating Tool for Perturbation Theory
  .... Materially Reduces Model Dependence
- NonPerturbative, Continuum approach to QCD
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- Method yields Schwinger Functions $\equiv$ Propagators

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Cross-Sections built from Schwinger Functions

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Schwinger Functions

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- Proving fruitful.

Persistent Challenge

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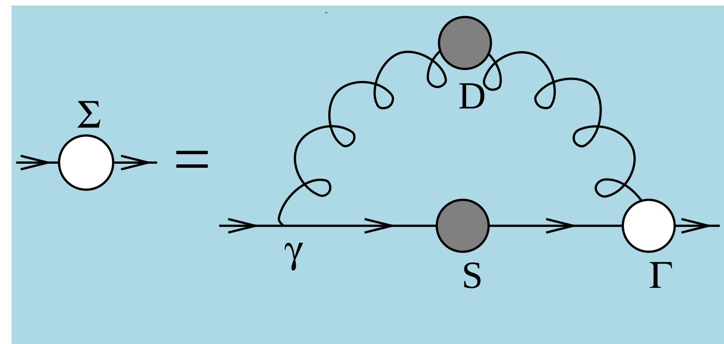
- Infinitely Many Coupled Equations



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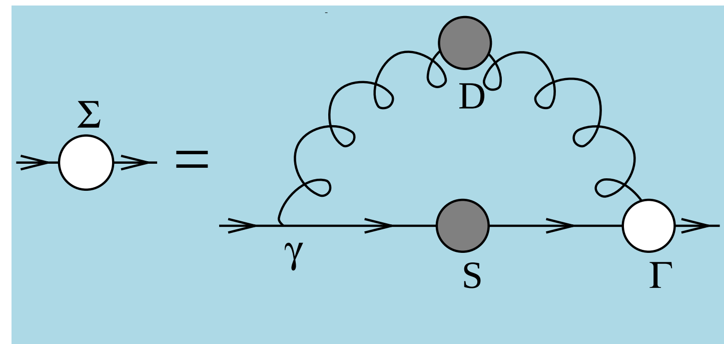

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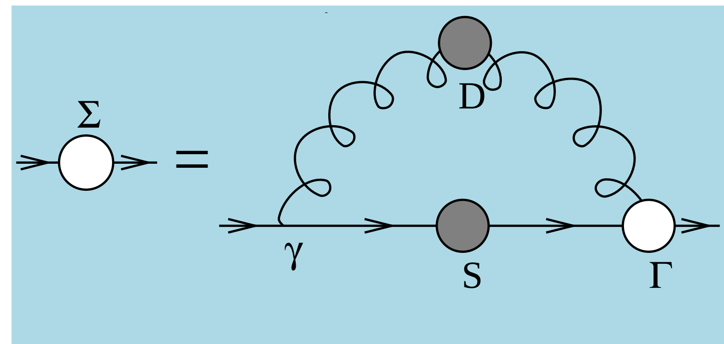

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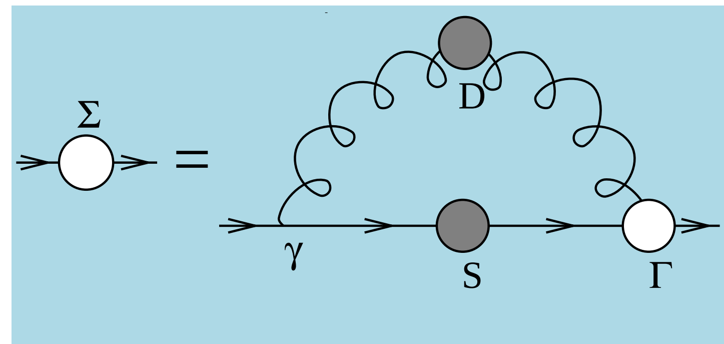

- Coupling between equations necessitates truncation
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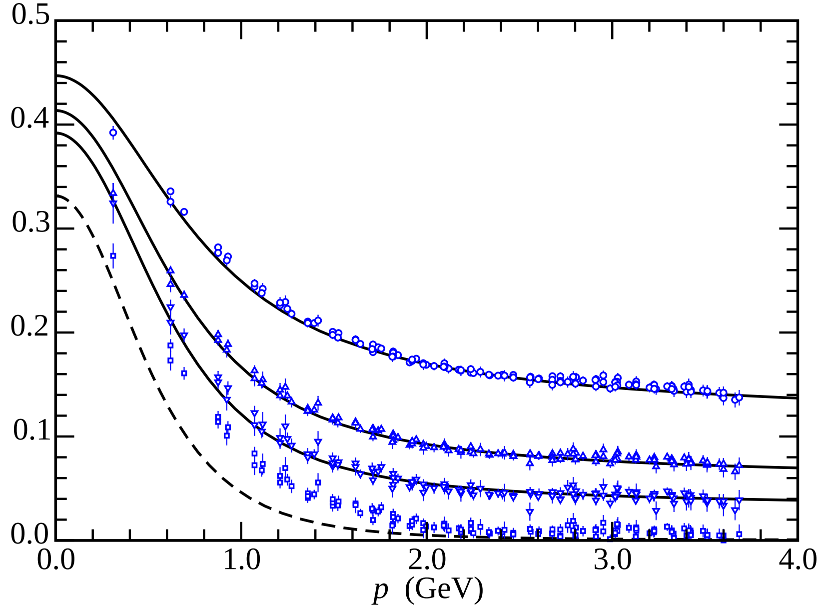
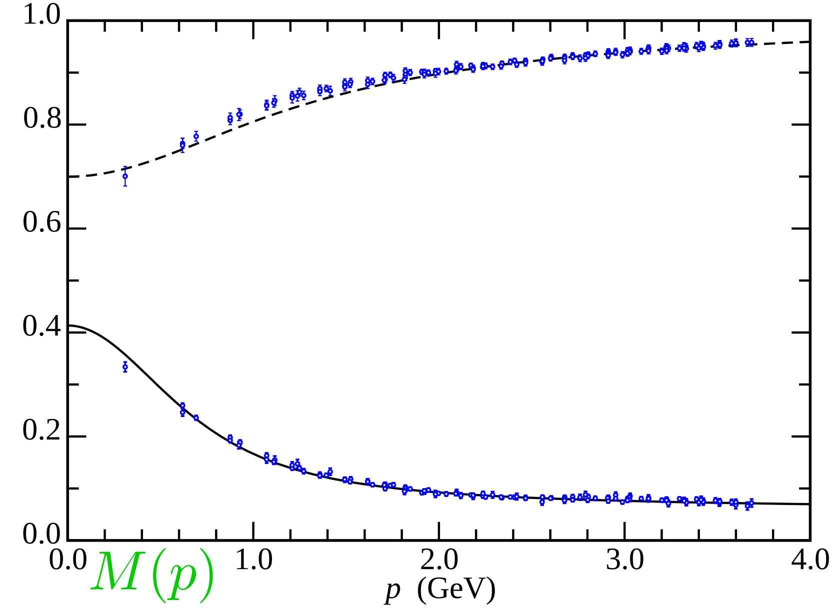
    Not useful for the nonperturbative problems
    in which we're interested

Quenched-QCD Dressed-Quark Propagator

$M(p)$ $Z(p)$





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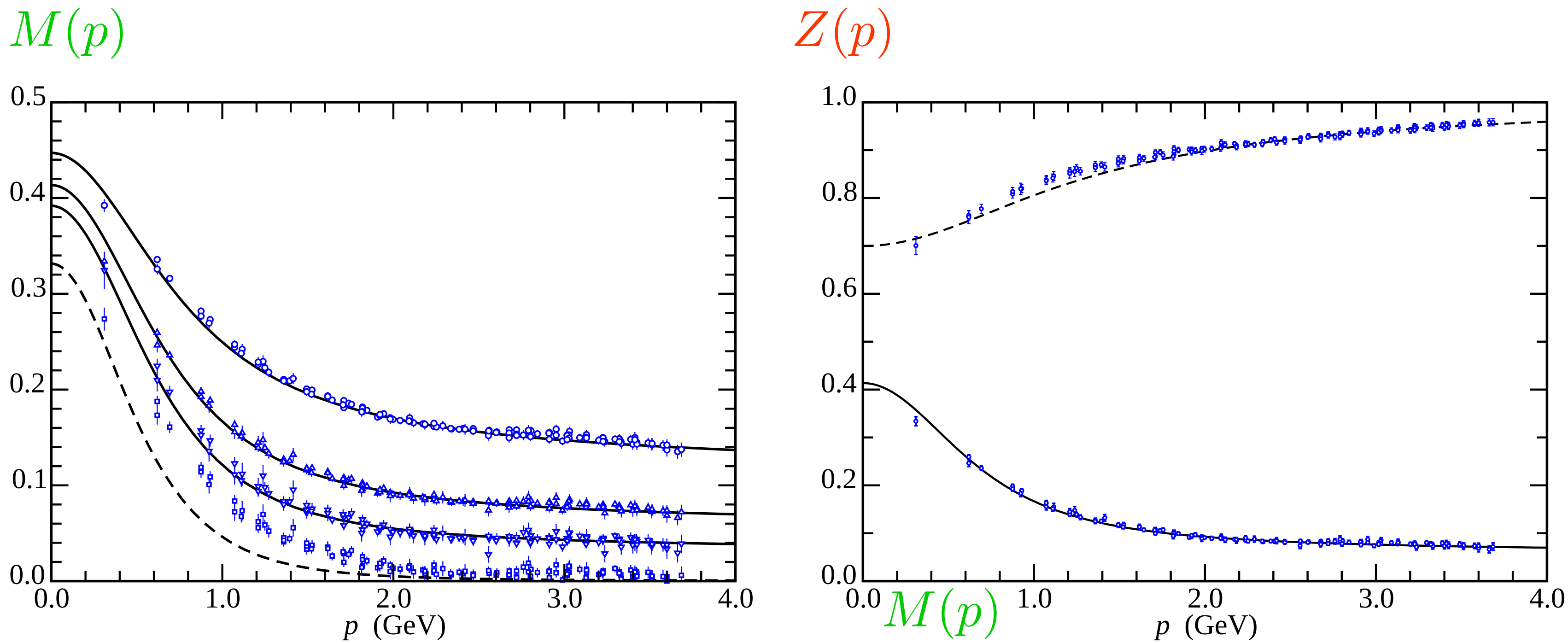
Quenched-QCD Dressed-Quark Propagator

2002



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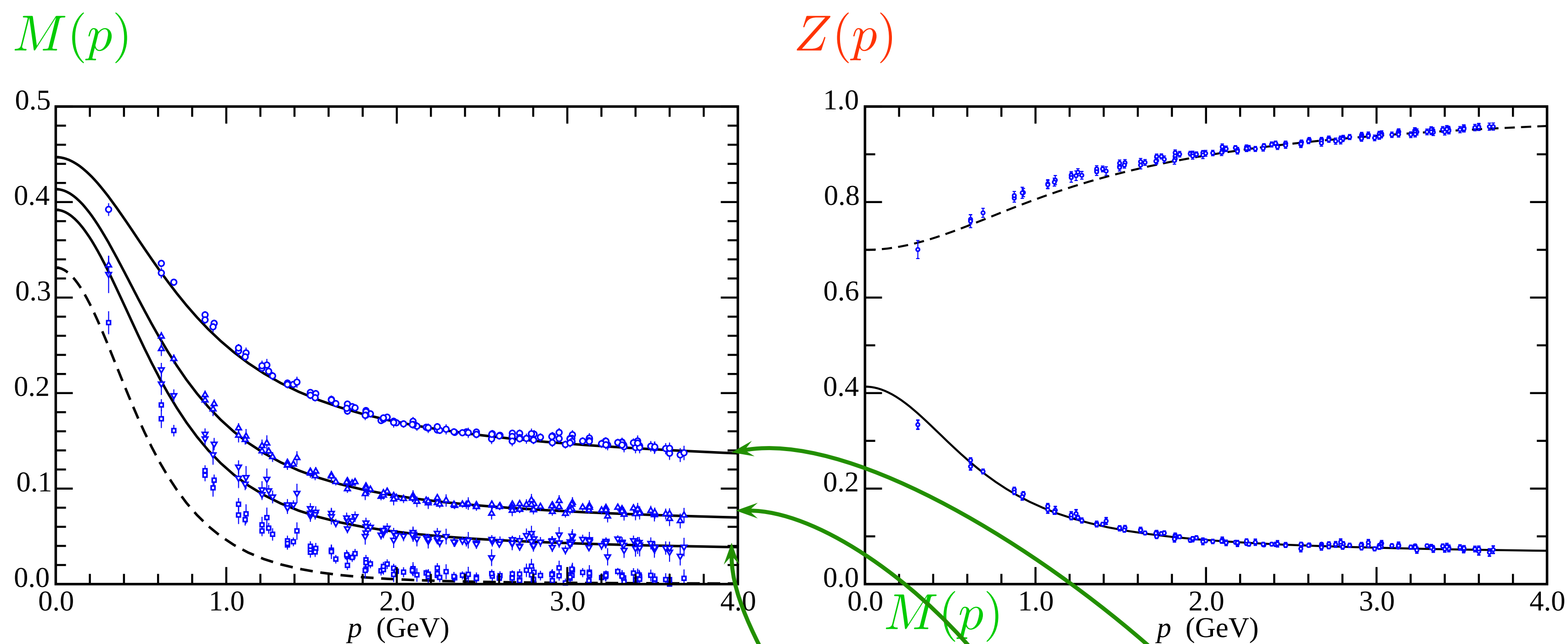

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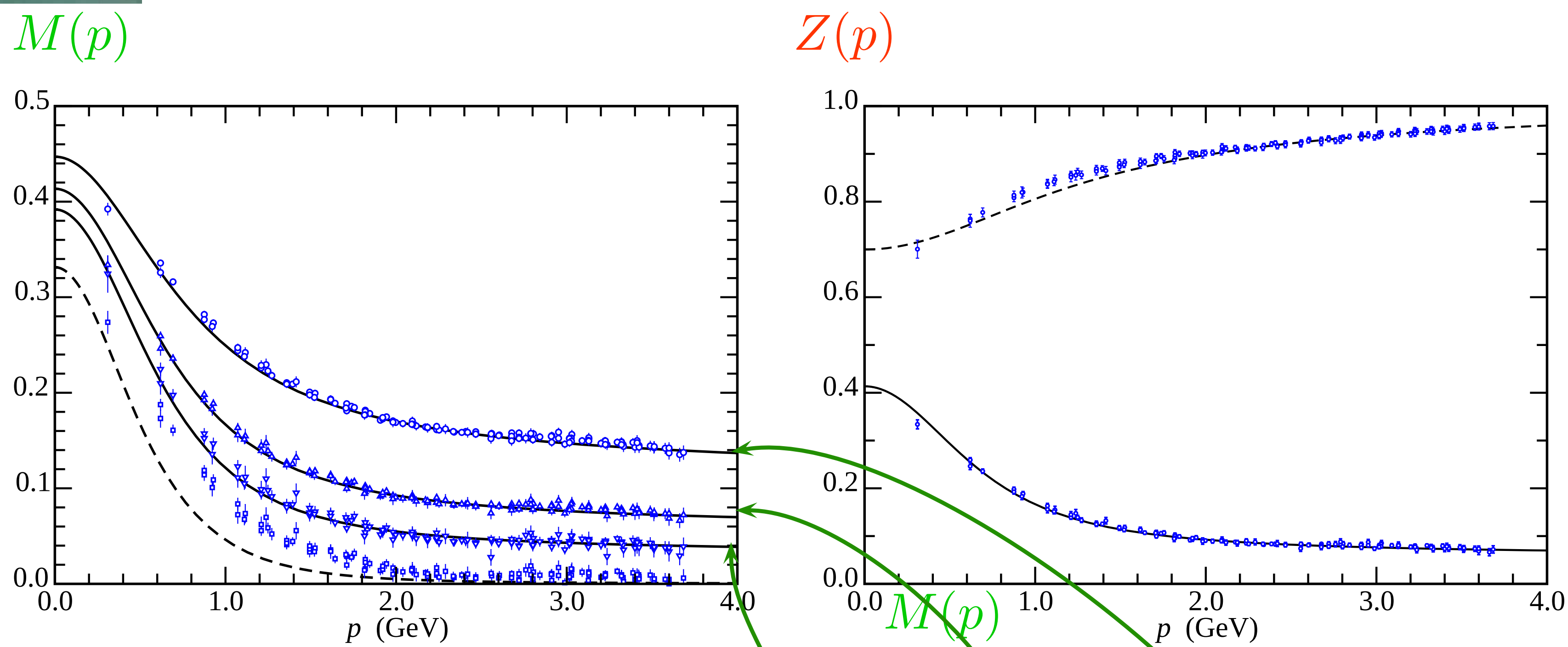

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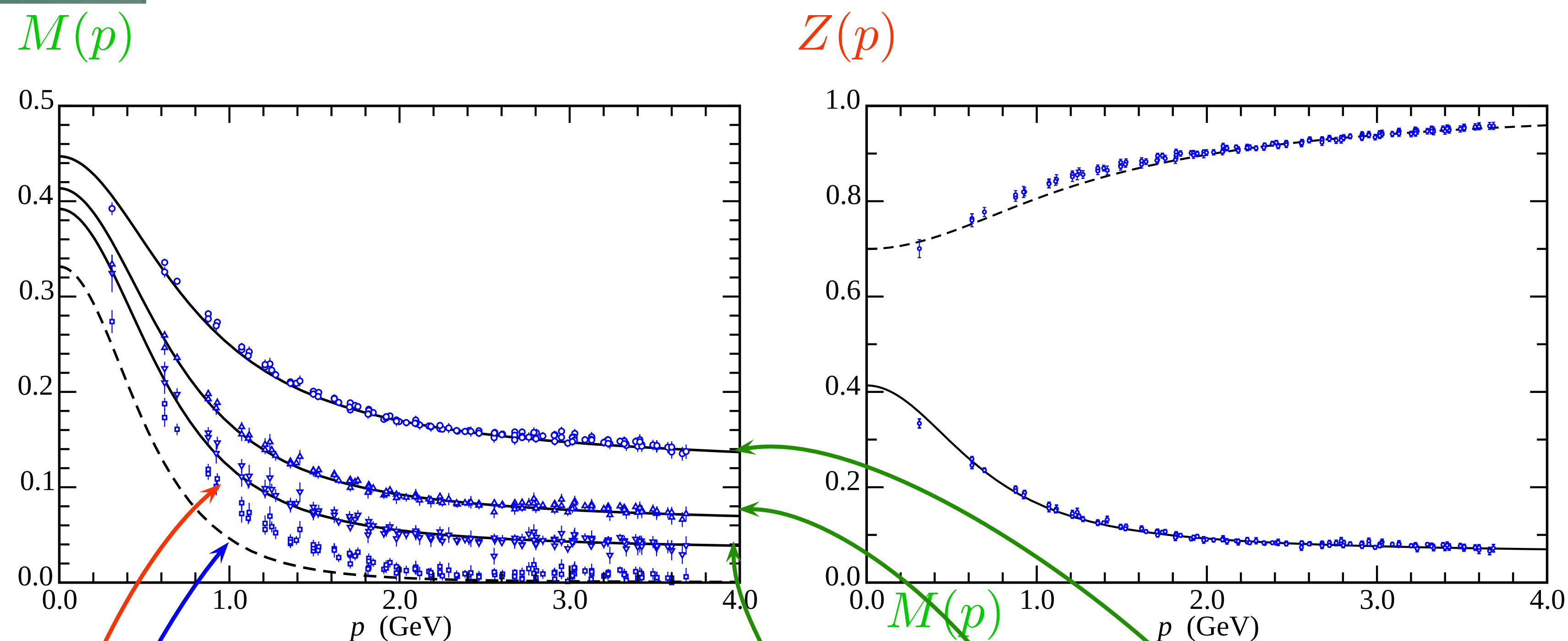

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- Linear extrapolation of lattice data to chiral limit is inaccurate

McNeile and Michael
he-la/0607032

Radial Excitations & Lattice-QCD

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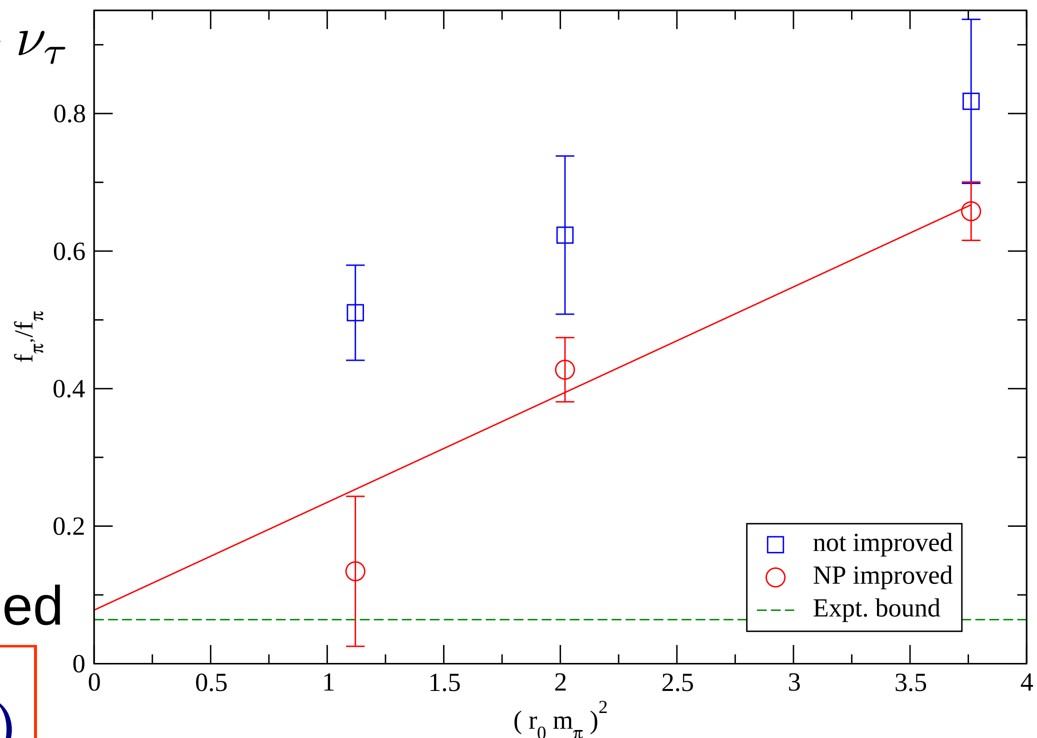
$$\boxed{\Rightarrow \frac{f_{\pi_1}}{f_\pi} = \mathbf{0.078\,(93)}}$$



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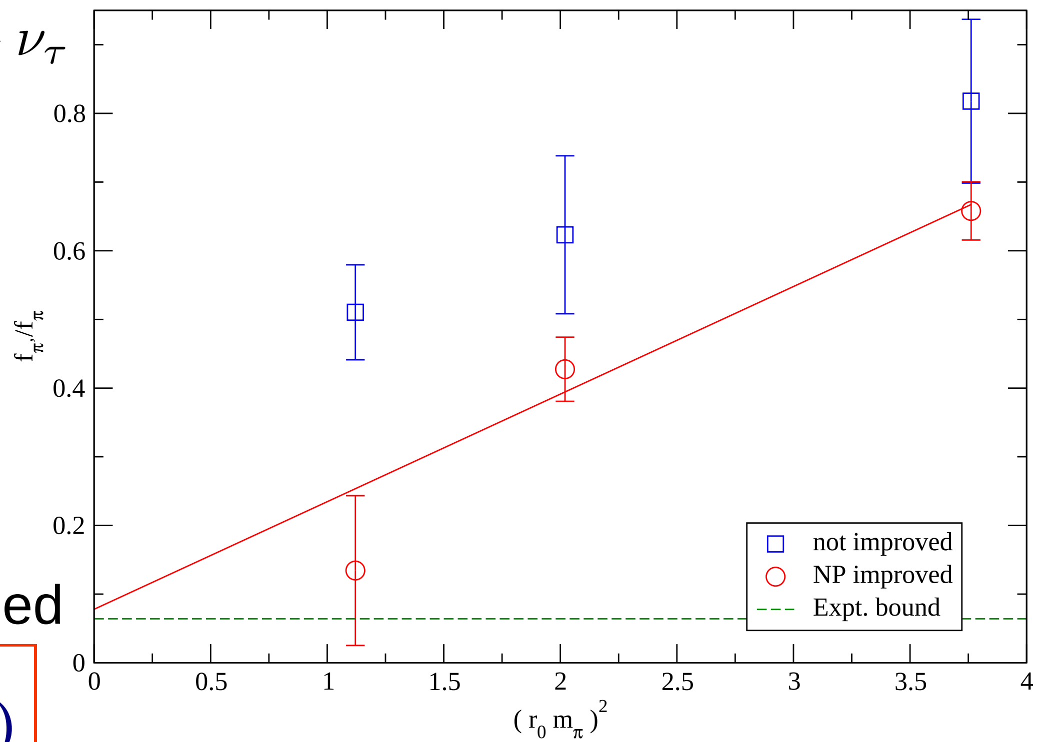

- Full ALPHA formulation is required to see suppression, because PCAC relation is at the heart of the conditions imposed for improvement (determining coefficients of irrelevant operators)

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Radial Excitations & Lattice-QCD

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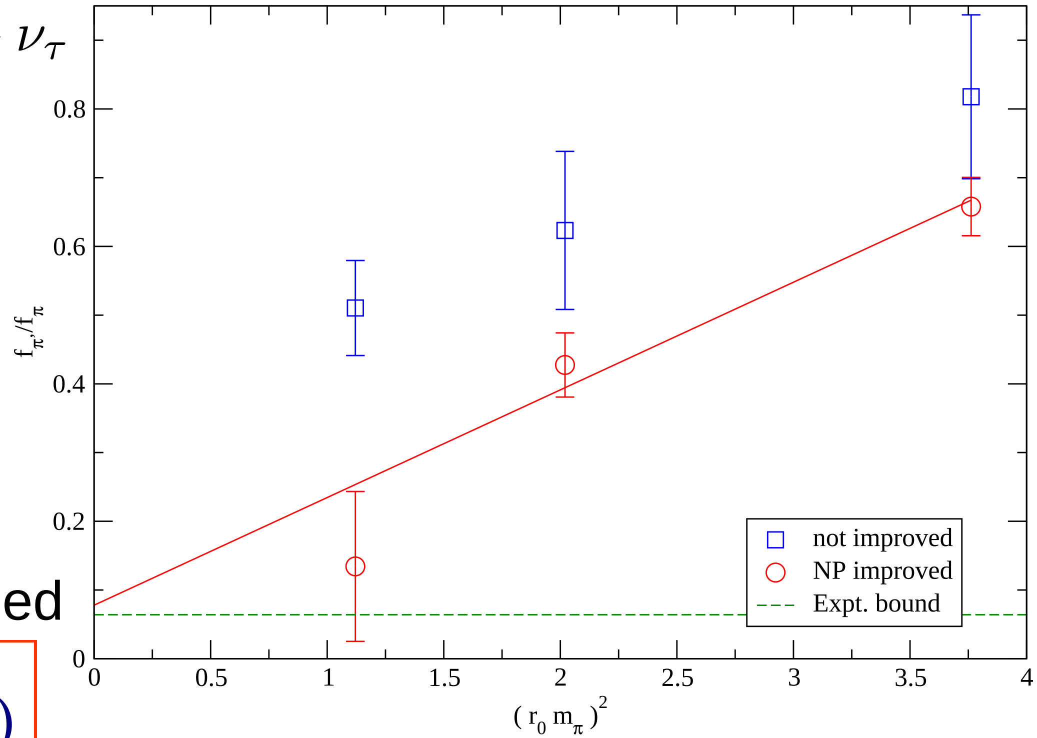
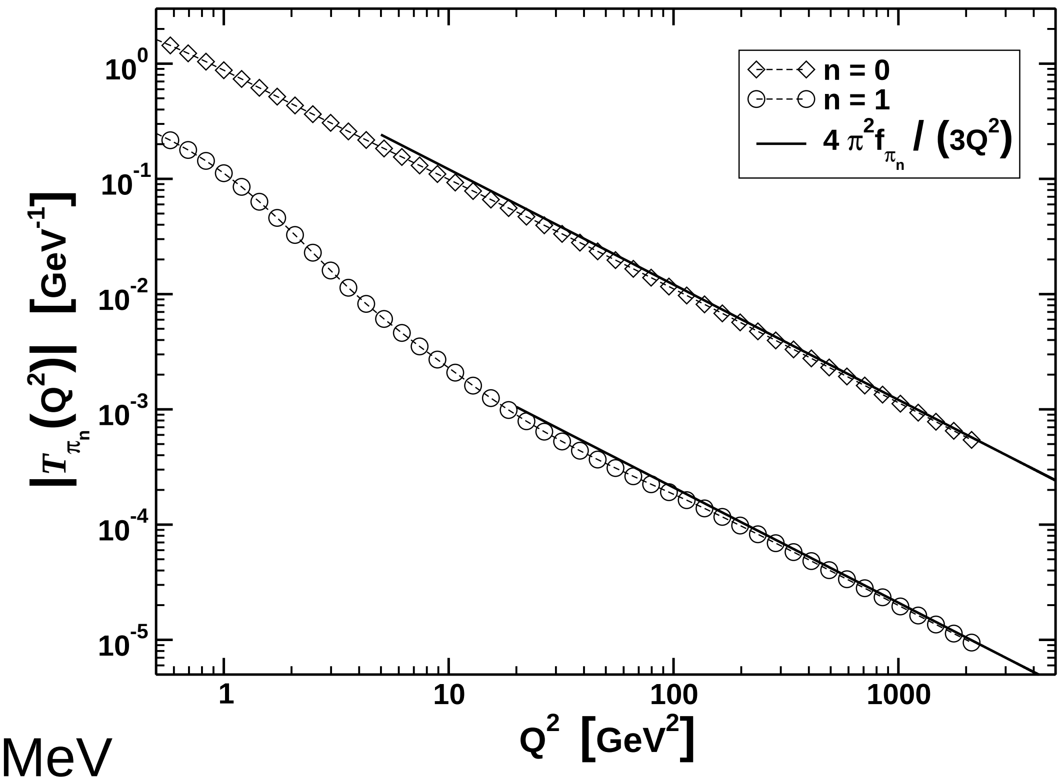


- *The suppression of f_{π_1} is a useful benchmark that can be used to tune and validate lattice QCD techniques that try to determine the properties of excited states mesons.*

Calculated Transition Form Factor: RGI Rainbow-Ladder

Höll, Krassnigg, Maris, *et al.*, "Electromagnetic properties of ground and excited state pseudoscalar mesons," nu-th/0503043



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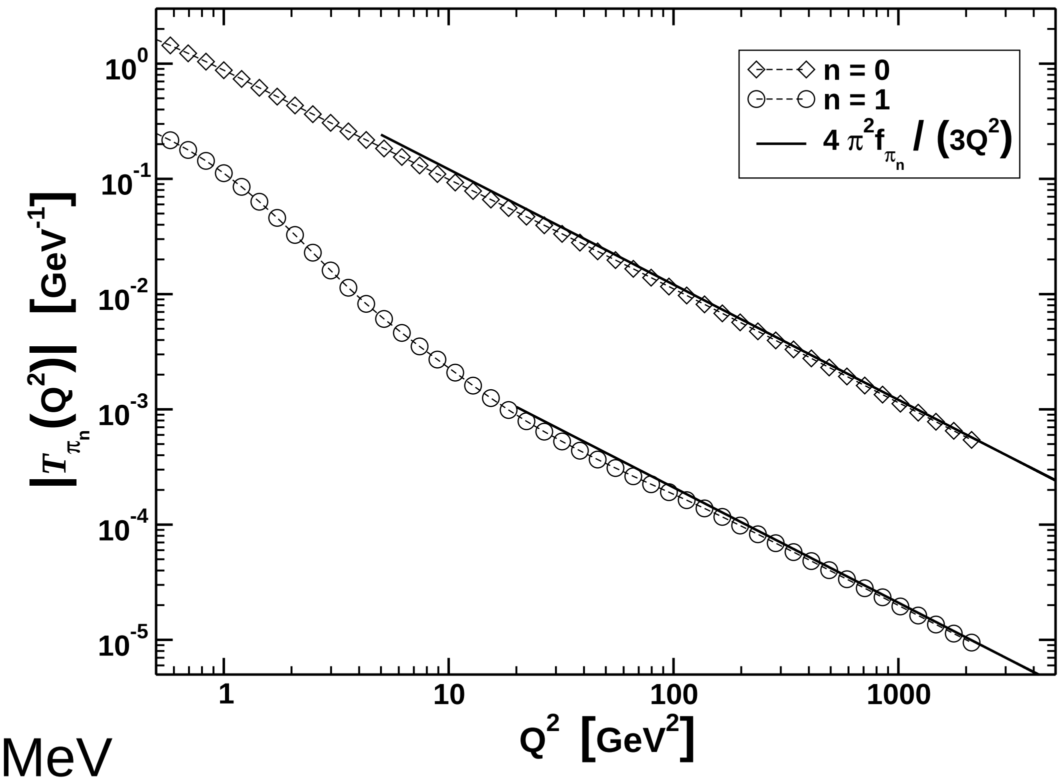

- $m_u(1\,\mathrm{GeV}) = m_d(1\,\mathrm{GeV}) = 5.5$ MeV
- Predicted UV-behaviour is abundantly clear
  - precise for $Q^2 > 120$ GeV^2

Harry Lee

Pions and Form Factors

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Pions and Form Factors

- Dynamical coupled-channels model . . . Analyzed extensive JLab data . . . Completed a study of the $\Delta(1236)$
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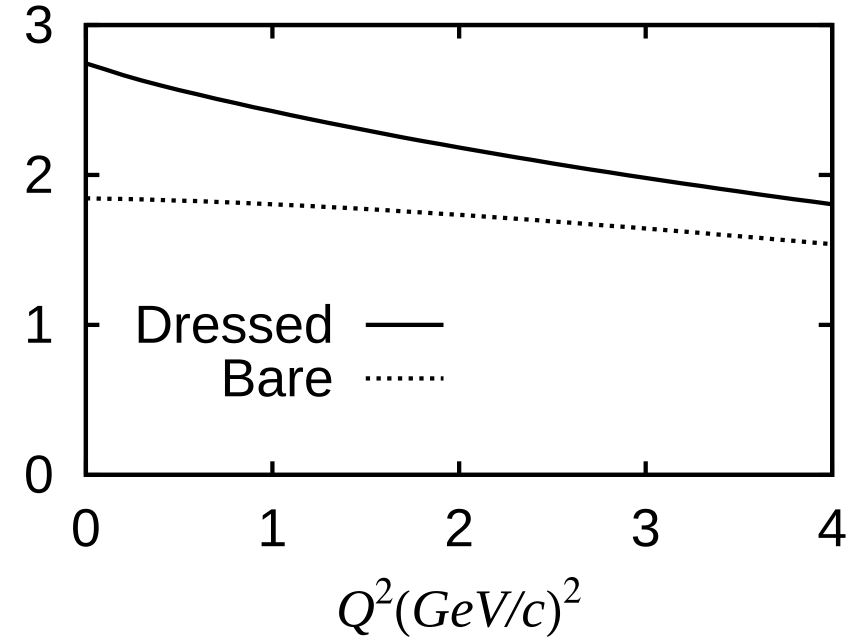
Ratio of the M1 form factor in $\gamma N \to \Delta$ transition and proton dipole form factor G_D. Solid curve is $G^*_M(Q^2)/G_D(Q^2)$ including pions; Dotted curve is $G_M(Q^2)/G_D(Q^2)$ without pions.



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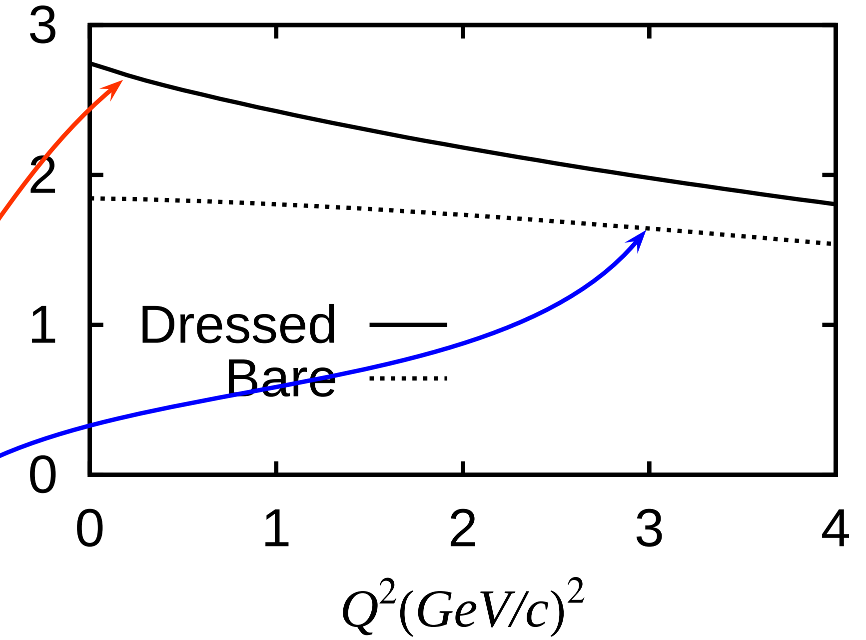
Quark Core



- Responsible for only 2/3 of result at small Q^2
- Dominant for $Q^2 > 2 - 3\,\text{GeV}^2$

Results: Nucleon and Δ Masses

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Mass-scale parameters (in GeV) for the scalar and axial-vector diquark correlations, fixed by fitting nucleon and Δ masses

Set A – fit to the actual masses was required; whereas for

Set B – fitted mass was offset to allow for "π-cloud" contributions

set	M_N	M_Δ	m_{0^+}	m_{1^+}	ω_{0^+}	ω_{1^+}
A	0.94	1.23	0.63	0.84	0.44=1/(0.45 fm)	0.59=1/(0.33 fm)
B	1.18	1.33	0.80	0.89	0.56=1/(0.35 fm)	0.63=1/(0.31 fm)

- $m_{1^+} \to \infty$: $M_N^A = 1.15$ GeV; $M_N^B = 1.46$ GeV

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- Constructive Interference: 1^{++}-diquark + $\partial_\mu \pi$

Deep-inelastic scattering

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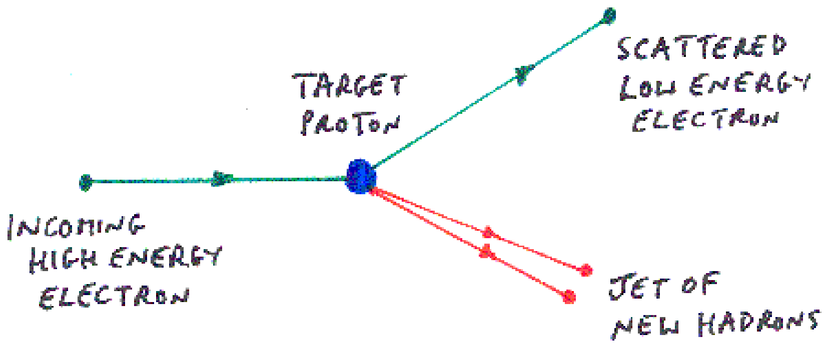
- Looking for Quarks

Deep-inelastic scattering



- Looking for Quarks

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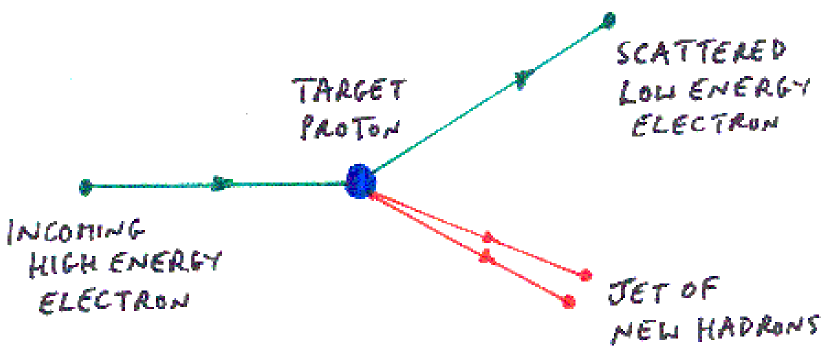

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- Signature Experiment for QCD:
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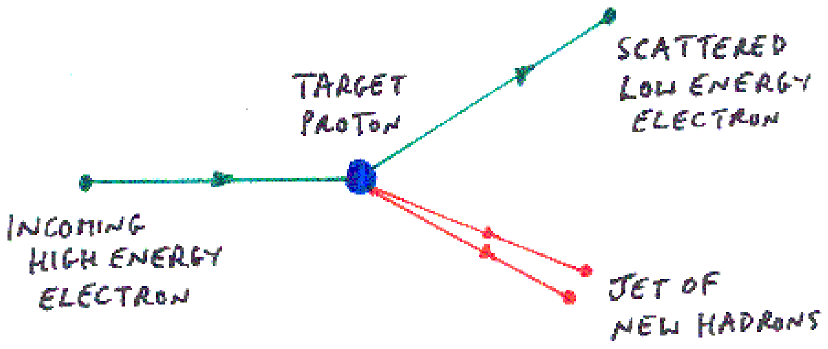

- Looking for Quarks

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- Cross-section: Interpreted as Measurement of Momentum-Fraction Prob. Distribution: $q(x)$, $g(x)$

Pion’s valence quark distn

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- However, NO π Targets!

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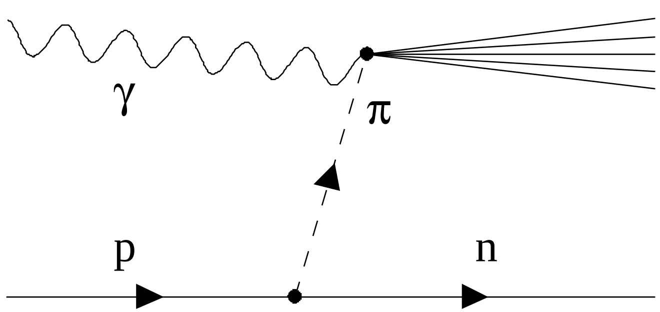
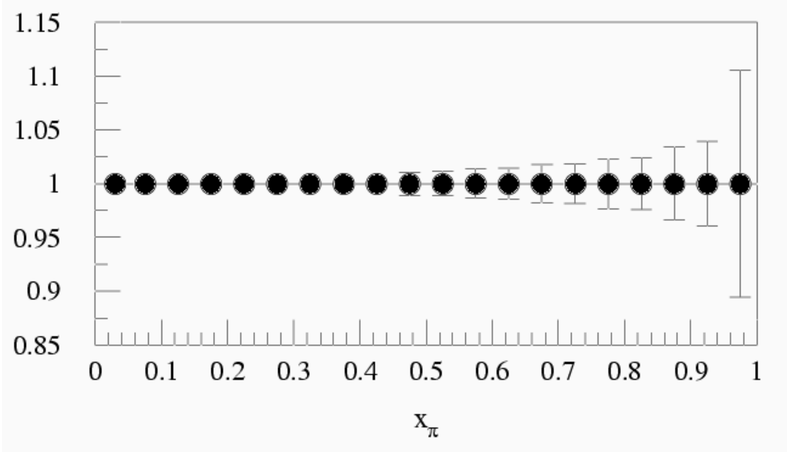
- Proposal (Holt & Reimer, ANL, nu-ex/0010004)

  $e^-_{5\,\mathrm{GeV}} - p_{25\,\mathrm{GeV}}$ Collider $\to$ Accurate "Measurement"





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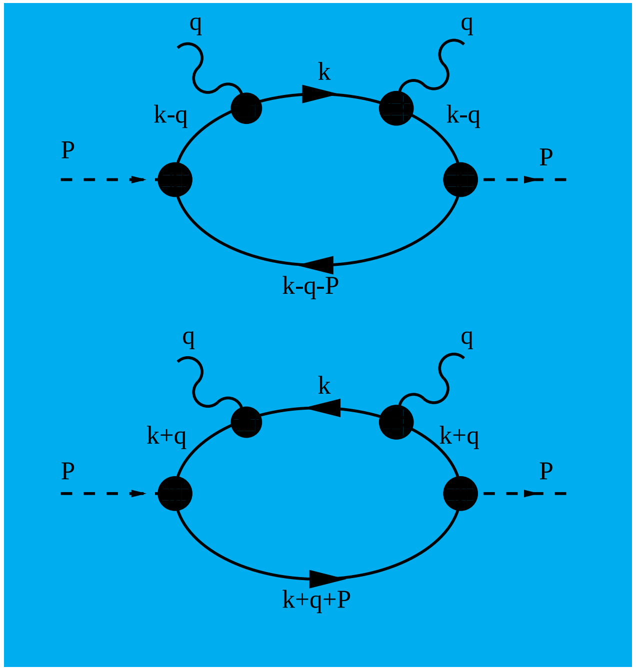
Handbag diagrams



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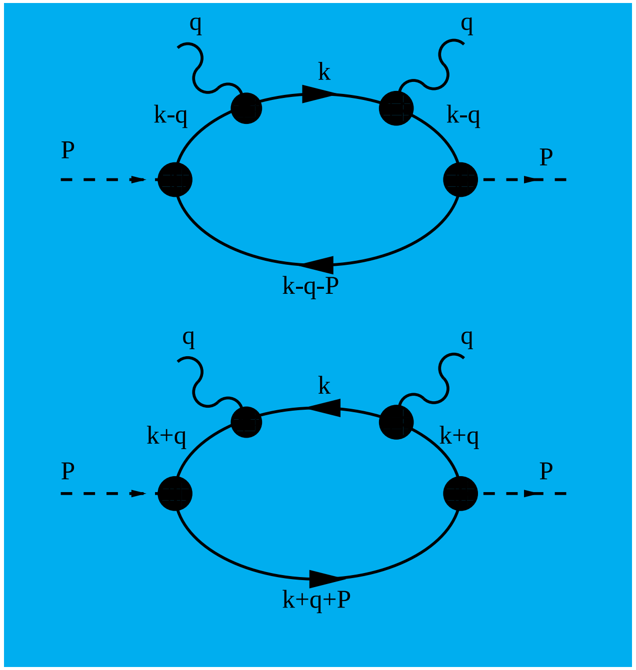

$$W_{\mu\nu}(q;P) = \frac{1}{2\pi}\mathrm{Im}\left[T^{+}_{\mu\nu}(q;P) + T^{-}_{\mu\nu}(q;P)\right]$$

$$T^{+}_{\mu\nu}(q,P) = \mathrm{tr}\int\frac{d^4k}{(2\pi)^4}\,\tau_{-}\bar{\Gamma}_{\pi}(k_{-\frac{1}{2}};-P)\,S(k_{-0})\,ieQ\Gamma_{\nu}(k_{-0},k)$$
$$\times S(k)\,ieQ\Gamma_{\mu}(k,k_{-0})\,S(k_{-0})\tau_{+}\Gamma_{\pi}(k_{-\frac{1}{2}};P)\,S(k_{--})$$

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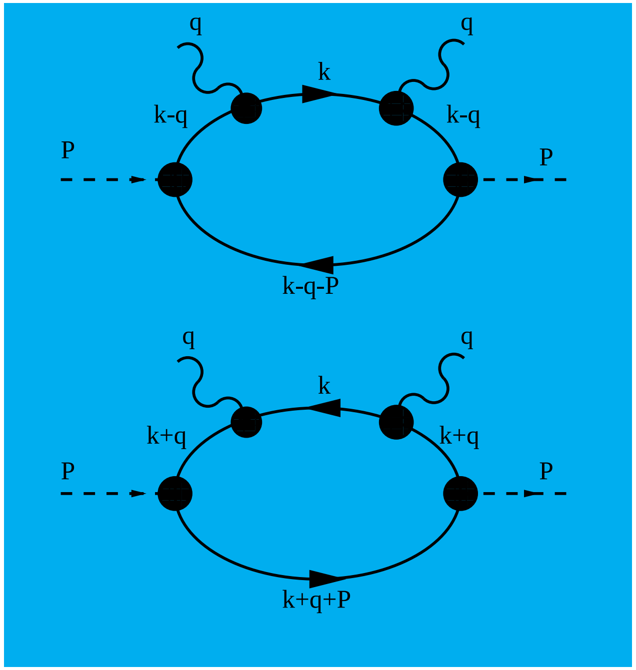
Handbag diagrams

Bjorken Limit: $q^2 \to \infty\,, \quad P\cdot q \to -\infty$

but $x := -\dfrac{q^2}{2P\cdot q}$ fixed.

Numerous algebraic simplifications



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\end{aligned}
$$

Extant theory vs. experiment

K. Wijersooriya, P. Reimer and R. Holt,
nu-ex/0509012 ... Phys. Rev. C (Rapid)